DOCUMENT RESUME

ED 196 669 SE 033 211

AUTHOR	Atkin, J. Myron; Wyatt, Stanley P., Jr.
TITLE	Gravitation, Book 3. The University of Illinois Astronomy Program.
INSTITUTION	Illinois Univ., Urbana.
SPONS AGENCY	National Science Foundation, Washington, D.C.
PUB DATE	69
NOTE	113p.; For related documents, see SE 033 210-213.
EDRS PRICE	MF01/PC05 Plus Postage.
DESCRIPTORS	*Astronomy; Elementary Education; Elementary School Science; Junior High Schools; *Physical Sciences; *Science Activities; Science Curriculum; Science Education; Science History; *Science Programs
IDENTIFIERS	*University of Illinois Astronomy Program

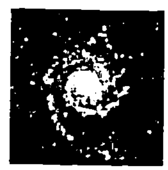
ABSTRACT

Presented is book three in a series of six books in the University of Illinois Astronomy Program which introduces astronomy to upper elementary and junior high school students. The causes of celestial motion are investigated and the laws that apply to all moving things in the universe are examined in detail. Topics discussed include: the basic concepts of speed, acceleration, force and mass; gravity at the earth's surface; Newton's law of universal gravitation; orbital paths near the earth; and the motions and masses of planets and stars. (Author/DS)

THE UNIVERSITY OF ILLINOIS ASTRONOMY PROGRAM

GRAVITATION

CODIRECTORS: J. MYRON ATKIN STANLEY P. WYATT, JR.



BOOK 3

1817

Harper & Row, Publishers

New York Evanston London

Illustration: Jim and Muriel Collins, Paul Hazelrigg

Cover: THE SPIRAL GALAXY NGC 628 IN PISCES photographed through the 200-inch Hale telescope at Mount Palomar, California

Fritz Goro, Black Star, *Albert Einstein*, page 98. Historical Pictures Service, Chicago, *Isaac Newton*, page 6; *Galileo*, page 17. Lowell Observatory, *Percival Lowell*, page 96. Mount Wilson and Palomar Observatories, *The Moon*, page 10; *The Great Galaxy in Andromeda*, page 107; *Three Galaxies*, page 110.

Printed in the United States of America

PREFACE

Have you ever asked yourself what keeps the moon in the sky? Thousands of years ago men asked themselves this question. Why, they wondered, didn't the moon fall to earth like other objects? They thought about it, but they could not reach a completely satisfactory explanation. Early in the seventeenth century, Johannes Kepler concisely described the motions of the moon and the planets. Yet Kepler's three laws of planetary motion did not explain *why;* they merely told how orbiting bodies behaved.

Then, towards the end of the seventeenth century, Isaac Newton published his famous *Principia*, one of the most significant contributions to science ever made. Newton is perhaps the greatest mathematician and scientist the world has known. In a burst of creative activity when he was 24 and 25 years old, he worked out his laws for motion and gravitation. These laws, with great simplicity, explained the motion of all objects and the force of gravitation that operates between all objects.

Newton's laws not only explained the moon's motion around the earth and the planets' motions around the sun; they also explained the motion of all objects, no matter where they were in the universe. His laws apply to celestial motions that have been going on for billions of years, and they apply to the latest spacecraft orbiting the earth or heading for some distant planet.

In *Gravitation*, you will follow the steps of Newton as you build an understanding of motion and gravitation. You will start with basic ideas of speed, acceleration, force, and mass. You will undertake activities that will lead to a concept of motion and gravitation that covers objects on the earth as well as far-off galaxies speeding through the universe.

Gravitation is the third in a series of six books that make up THE UNIVERSITY OF ILLINOIS ASTRONOMY PROGRAM. The program has been developed by professional astronomers and science educators to stimulate your interest in some of the basic concepts of astronomy. Your knowledge of these concepts will lead you to a greater awareness of the universe in which you live—a universe that is more understandable because of Isaac Newton.

PROJECT STAFF

The University of Illinois Astronomy Program is the product of eight years of research and development by the Elementary-School Science Project, a course content improvement project supported by the National Science Foundation. The program grew within a logical framework that incorporated writing conferences, classroom trials, evaluation reviews, and rewriting sessions. The staff of professional astronomers and science education specialists was under the direction of J. Myron Atkin, professor of science education, and Stanley P. Wyatt, Jr., professor of astronomy, both of the University of Illinois.

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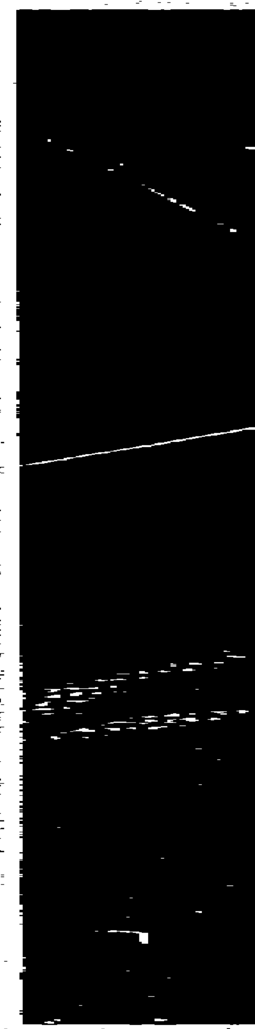

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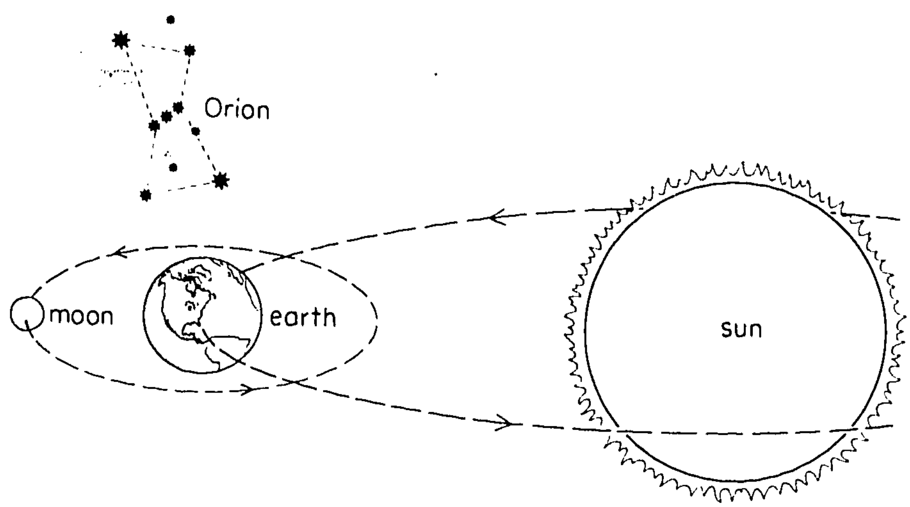
CHAPTER 1

Motion and Common Sense

The earth spins. The moon is in orbit. The sun streaks toward the star Vega at 12 mi/sec. In the winter sky the constellation Orion rises in the east and travels through the night toward the west. The Big Dipper circles slowly around the North Star every day. As the months go by, the sun seems to glide eastward through the constellations. The universe is in constant motion: nothing stands still.



For a long time astronomers have been able to chart the universe. They have determined the distance to the moon within a few miles and they have predicted centuries in advance the dates when the moon will eclipse the sun.

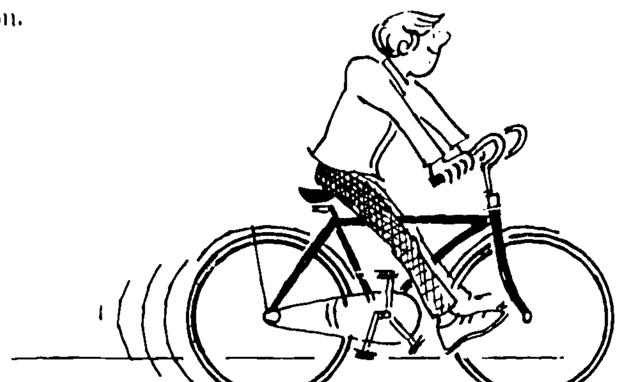
Long ago, astronomers discovered some rules to describe how the members of the solar system are moving. Every planet travels along an ellipse, with one focus of the ellipse at the sun. When a planet is closer to the sun, it travels more quickly than when it is farther away.

But one puzzle lingered longer than many of the others. Motion takes place—endlessly. Why? What makes an object move? What makes the moon orbit steadily around the earth and the planets around the sun?

Each object, some said, has its own natural place in the universe. This place determines the object's motion. According to this view, there is a sharp difference between motion on earth and motion in the heavens. Near the earth, light airy objects belong up. Heavy ones belong down. Motion occurs when you do something violent—when you force something out of its natural place. When you throw a rock, you are violently pushing it through the air. Only the downward drop is natural. The horizontal motion results from a force.

Motion in the heavens, however, was explained in a different way. Most people thought that the sun, the moon, the stars, and the planets moved along naturally in the only perfect way—in circles. These objects did not need to be pushed along. They required no force to keep them going.

By this reasoning, you could say that a falling stone requires no force. Nor does a rising balloon nor an orbiting planet. Motion is natural if an object is returning to where it belongs. Explanations are needed only when objects do not move in a natural way—when heavy objects start moving upward, or light ones downward, or when heavenly bodies stop moving in circles. Only then must we look for forces that cause the motion.



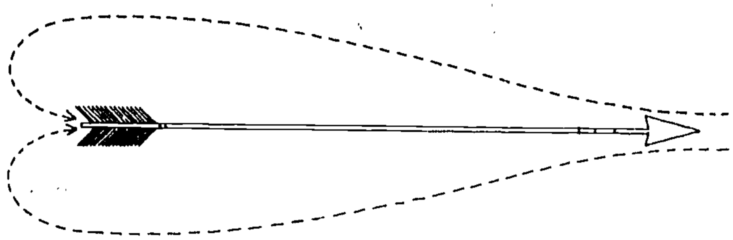
If you believe that each object moves toward some natural location in the universe, that each object has its own place, then your astronomy consists of finding the natural spot for each planet, for each star, for any astronomical body that interests you. According to this idea, an object's motion depends on the object. Stars don't move the way rocks do. The sun moves differently from smoke.

This idea of motion seems like common sense. When you place a book on the floor and push it, the book moves for a while. Then it stops—naturally. If you want the book to keep moving, you keep pushing it. In fact, when you see any earthly object in motion, it seems that some force has been exerted on the object. If there is not force, there seems to be no motion. If you pedal your bicycle, the bicycle rolls. If you stop pedaling, it stops—at least after a while.

Does the same reasoning apply to a ball you throw or an arrow you shoot? True, a force starts each one moving. You exert your muscles to heave a ball. The tight string on a bow starts the arrow flying through the air. One push keeps each of these objects moving for several seconds. If you believe that objects move only when a violent force is exerted on them, you must search for a force that *keeps* the objects moving.

Aristotle, a Greek scientist who lived more than two thousand years ago, had an explanation. He thought that as an arrow flies, the air from the tip of the arrow swishes to the tail. According to his idea, what keeps the arrow in flight?

Today we can test Aristotle's idea by performing experiments. We can throw a ball or shoot an arrow when there is no air. According to Aristotle, would an arrow fly in a vacuum? We can also test Aristotle's idea by simply asking a question. If Aristotle was right, why does an arrow flying through the air lose speed and fall to the ground? This



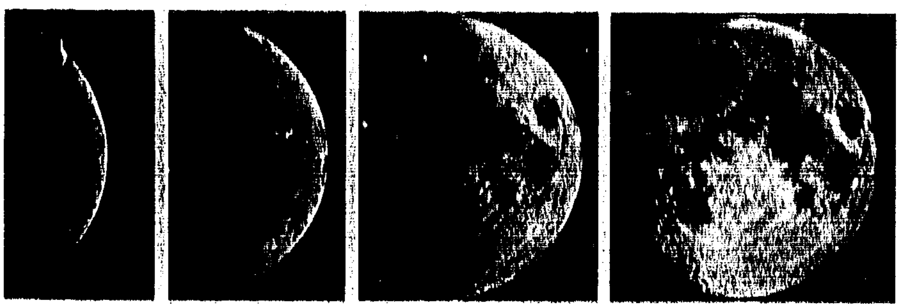
question couldn't be answered easily. More than a thousand years passed before a few scientists began to doubt some of Aristotle's ideas and to search for better ways to explain the causes of motion.

The study of motion presented puzzles to curious scientists for centuries. Forces are needed to move a rock up, but not to move a rock down. After all, you don't have to push a rock to make it go down. It goes down naturally. Doesn't such an idea seem like common sense? Some scientists wondered.

Once an object starts moving, a steady force is needed to keep it going. A book doesn't slide along the floor forever. Soon it will come to a stop. Such an idea seems like common sense. But some scientists wondered.

The moon moves endlessly across the sky. Nothing seems to be pushing it. No force is needed. The moon just naturally moves that way. Such an idea seems like common sense. But some scientists wondered.

Ideas about motion changed over the centuries because scientists wondered. In this book you will find out how and why beliefs about motion changed. You will learn why objects move in orbit through space. And you will hear about some of the men who advanced our understanding of why the universe moves as it does.



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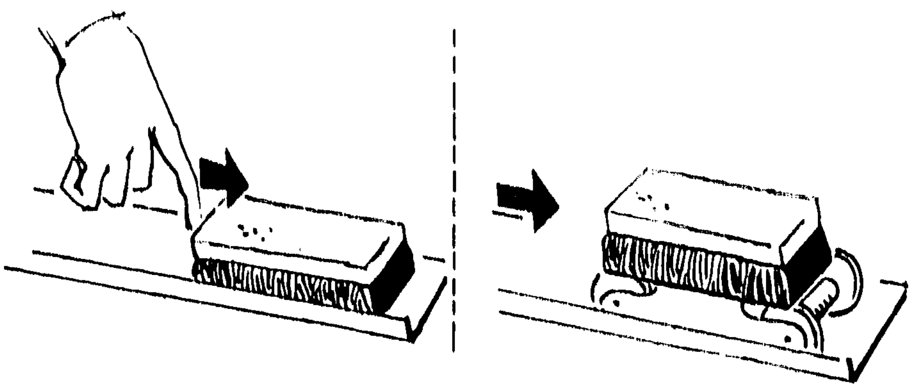
CHAPTER 2

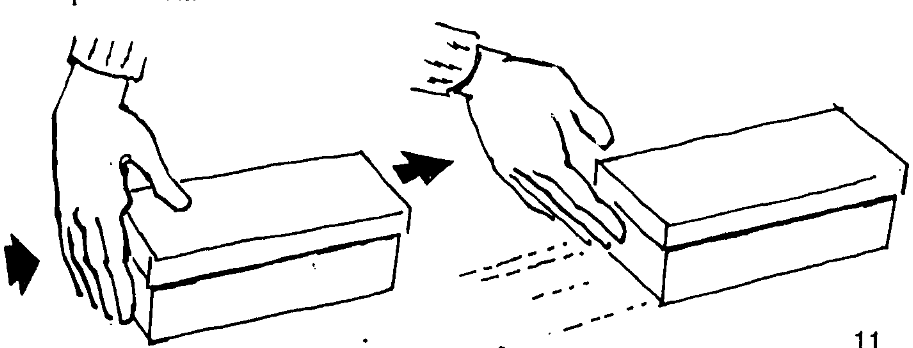
Straight and Steady

Common sense tells you that you have to push an object to keep it moving or turning. But now think of an eraser in the chalk tray. You give it a little push and it slides a short way down the tray. If you were to put the eraser in a little cart and give it the same amount of push, it would go farther. If you oiled the wheels of the cart and cleaned all the chalk dust away, the eraser would go even farther. You have the feeling that if the tray were long enough and smooth enough, the cart and eraser would go a very long way indeed!



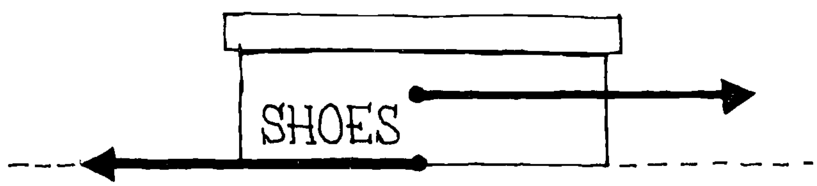
ACROSS THE FLOOR

Try pushing an empty shoe box across the floor. Think of the forces acting on the shoe box during its brief journey. To begin with, it moves at no speed at all. It takes a shove to get it started. But at the instant your hand and the box part, the box moves across the floor at a certain speed, perhaps 14 feet per second. You change its motion from 0 ft/sec to 14 ft/sec. The force of your push speeds up the box.



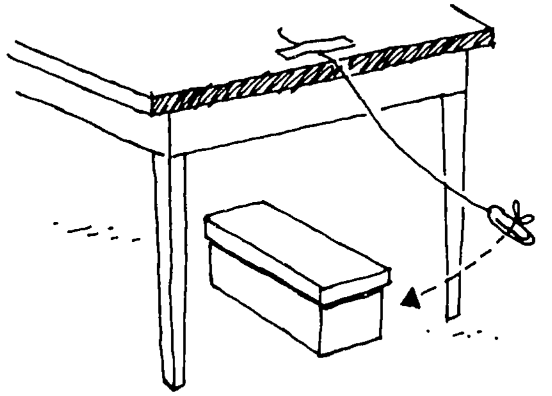
As soon as the box is moving, a different force pushes on it. A frictional force exerted by the floor acts to slow down the box. After a short distance it comes to rest. The box is slowed by the force of friction from a speed of 14 ft/sec to no speed at all. And the instant it comes to rest, the frictional force disappears.

We live in a world of friction. *Friction* is a force that resists motion. If the box is sliding eastward, the floor exerts a westward-pushing force on the box. The frictional force acts in the direction opposite the direction an object is moving.



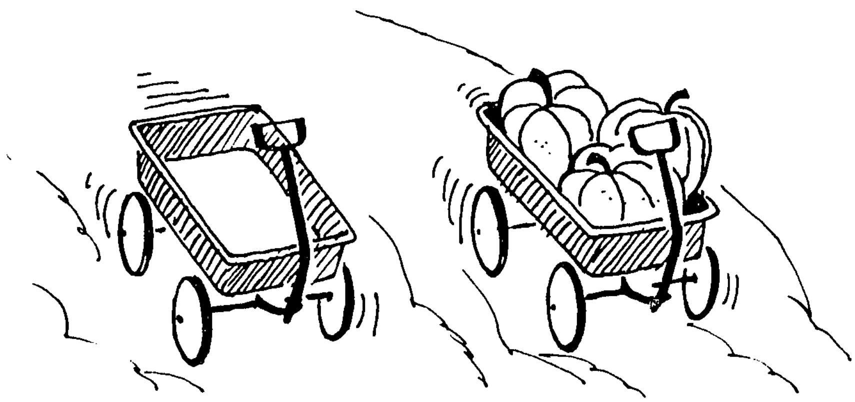
BIG STUFF, LITTLE STUFF

You have observed that a sliding shoe box is soon slowed down by frictional forces. And you know that friction acts opposite to the direction of motion. Would the amount of matter in an object make a difference in the way it might move? You can find out more about moving objects without interference from frictional forces.

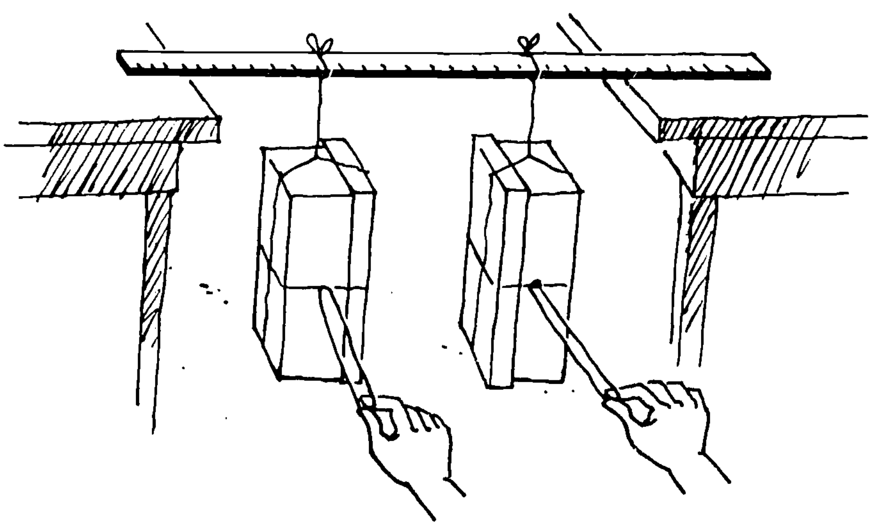


Suspend a paper clip on a string. Place an empty shoe box in the path of the clip. Lift the clip to a certain height and let it swing into the box. Watch the swinging clip. What happens to it when it collides? Pack a small lump of clay around the clip. Lift it to the same height as before and let it go again. What happens to the swinging object this time? Add still more clay and observe what happens. Try this activity using a ping-pong ball, and then a lump of clay the same size. What happens to the moving object each time? Would it be correct to say that bigger objects resist change in motion more than smaller ones?

Think about two wagons. One is empty, but the other one is loaded. Each is rolling down a hill at the same speed. Which one is easier to stop?



Find two shoe boxes the same size. Place some rocks in one box, but leave the other one empty. Tie each box with string and hang it from a yardstick as shown below. Attach a thin rubber band to each box to use as a rough measure of force. With the rubber band, pull the empty box. How much does the rubber band stretch? How much force is exerted on the box? Now do the same with the other box. Notice the stretch of the rubber band this time. How much force is needed to move this box?



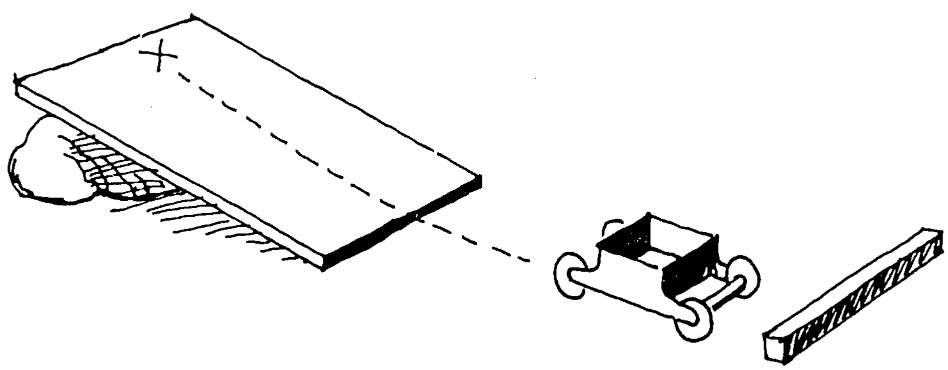
On the floor are two closed shoe boxes. One is empty; the other contains a brick. Kick the first box. Then kick the second box with the same strength. What happens?

You have two objects that look alike and are the same size. But somehow they are different. One moves readily when a force is exerted on it; the other offers more resistance. Why is there a difference in the way each one moves? Perhaps you will say that one box is light and one is heavy; or that there is more stuff in one box; or there is more matter in one.

Think of all the matter in an object as its *mass*. Mass is a basic property of any object. Wherever the object is placed — here on earth or far out in space — its mass stays the same. Mass is constant so long as no part of the object is removed or other matter added to it.

A star has a great deal of mass, a locomotive less, a tennis ball still less, and a speck of dust even less. The greater the mass of a stationary object, the more it tends to stay exactly where it is. The greater the mass of a moving object, the more it tends to keep going just as it is, moving in the same direction at the same speed. You can think of the mass of an object as its tendency to resist changes in motion.

Set up a smooth ramp. Roll a small cart or truck down the ramp and watch it move after it leaves the ramp. Because it has some mass, it tends to move straight across the floor at constant speed.



Friction doesn't slow it down very much. Now put a small obstacle, such as a wood stick, on the floor a few feet from the ramp. Roll the truck from the ramp again. Describe the motion of the truck before and after it collides with the obstacle. What did the stick do to the truck? Put some weight into the truck and try again. What did the stick do to the truck this time?

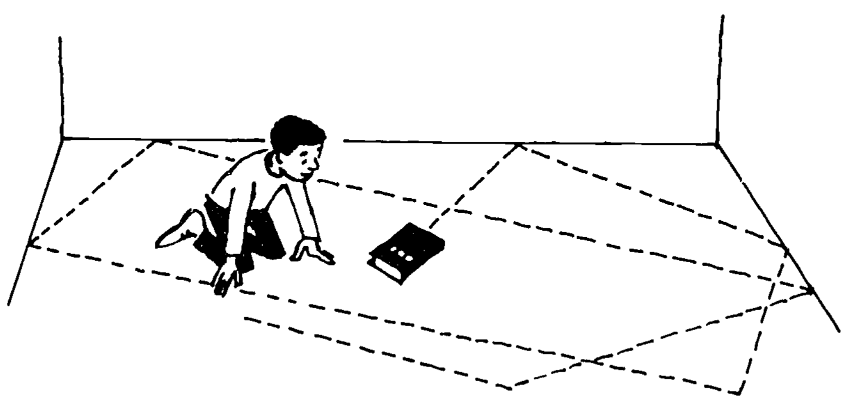
It was Galileo's (gal-eh-LAY-ohz) astonishing idea, back in the 1600's, that an object tends to remain at rest or to keep moving straight at constant speed unless a force of some kind compels it to move otherwise. The stick of wood exerted a brief force on the truck while the two were in contact, changing the motion of the rolling truck. If the stick had not been there, the truck would have kept going.

You have seen that if an object is at rest, it tends to remain at rest. If another object is moving, it tends to continue moving in the same direction at a steady speed. This tendency to move with an unchanging motion depends on the mass of the object. Only if a force acts on an object will its motion change. And the more massive a body, the harder it is to change its motion.

A WORLD WITHOUT FRICTION

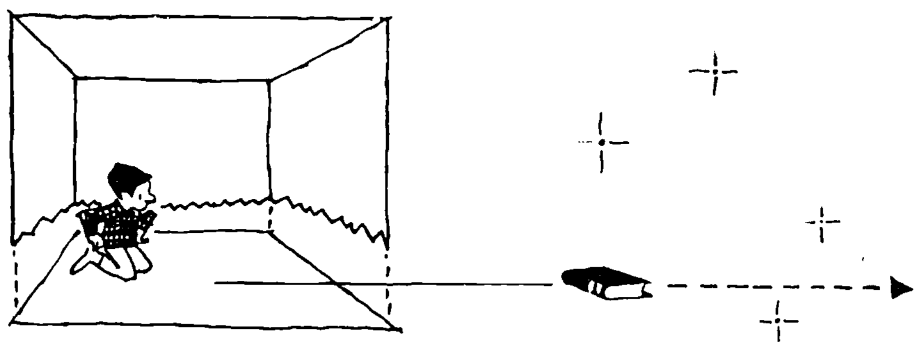
Imagine that there is no such thing as friction. Push a book across the floor. It keeps on going. There is no force to slow it down, so it keeps going until it bumps into the wall across the room. The wall exerts a brief force and changes the book's motion so that it bounces back across the room again. Back and forth it goes—forever.

Tear down all the walls and extend the floor for a mile or more. What does the book do? Without friction the book simply keeps going along at a fixed speed in a straight line.



Finally, imagine that the book is far out among the stars, far from any other object. There is scarcely any friction in space. After your push, no other forces are acting on the book, yet it continues to move. Can you describe its motion?

Without friction in space, how would you expect an isolated star to move? Practically no forces are exerted on such a star. So it keeps doing just what it was doing yesterday and the day before—moving at constant speed along a straight path.



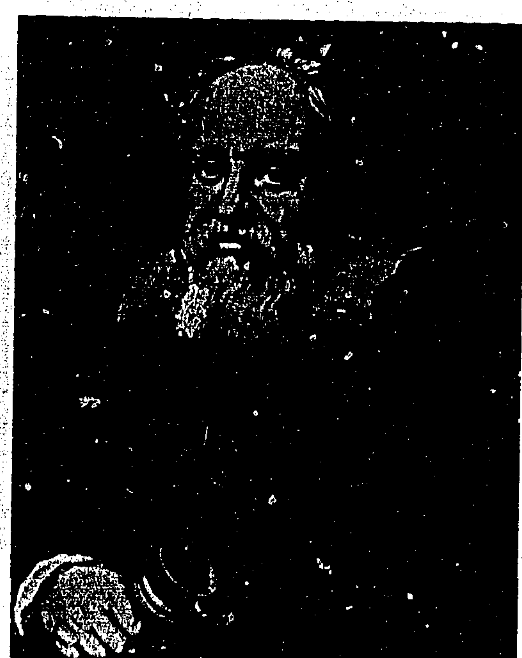
Remember some of Aristotle's ideas about motion. For almost two thousand years his ideas seemed like common sense. Why were we misled for so many years? Why did people continue to believe that you had to keep pushing an object to keep it moving in any other way than its "natural" way? Nobody took into account the effect of friction. Friction was the culprit—friction, the force that operates all around us here on earth, slowing down whatever is in motion.

Let's now turn outward to the universe of celestial bodies. Are things really entirely different out there than they are here on earth? Do objects naturally behave in an entirely different way out among the stars?

CHAPTER 3

Curved Motion

In his day, Galileo could not turn to the stars to make accurate observations of their motions. He had no way to find out whether his ideas about motion worked for stars as well as for rolling balls. But in more recent times, astonomers have been able to measure how a star moves.

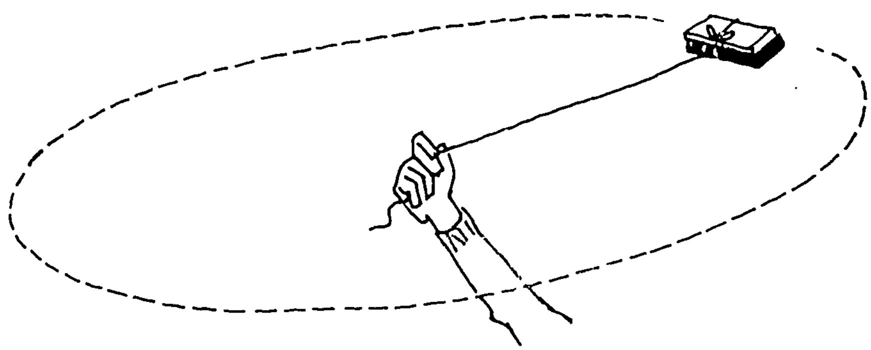


Galileo Galilei (1546-1642) tried to answer the question of why motion occurred. His investigations laid the groundwork for Newton's laws of motion.

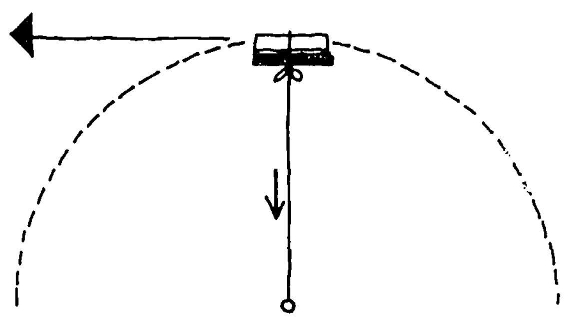
And every isolated star that has been observed carefully for many years has been found to move through space in a straight line at constant speed—as it should if Galileo's ideas are correct.

But what about other objects in space? Look at the moon; it is moving in a curved path around the earth every month. Jupiter's satellites are orbiting around their parent planet. Mars goes around the sun every 687 days. Man-made satellites close to the earth complete an orbit about every 90 minutes.

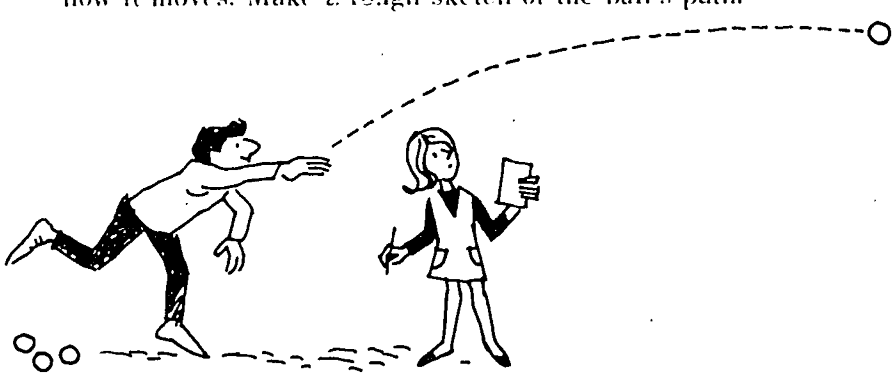
Tie one end of a 3-foot piece of string around an eraser. Make sure that the knot is good and tight, and that no one is in the way. Hold the other end of the string in your hand and start the eraser moving around your head at a steady speed. What kind of path does the eraser take? Can you explain why the eraser moves in this path?



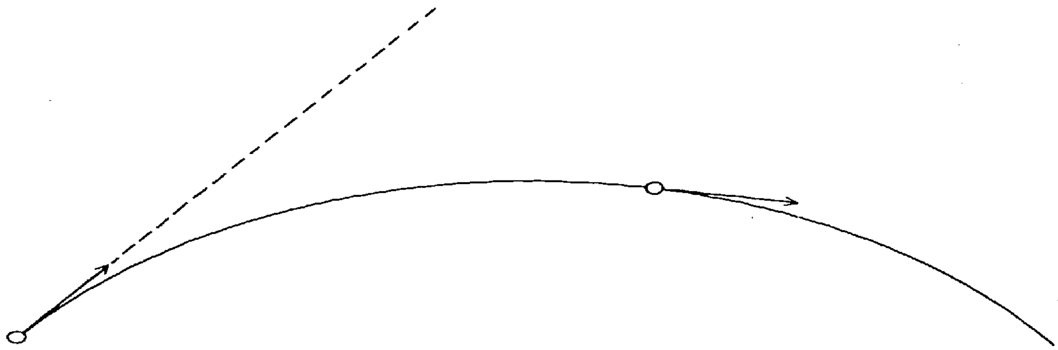
Look at the diagram below. The arrow tells something about the forward motion of the eraser. The string is exerting a force on the eraser. A small arrow shows the direction of this force. In what way does this force affect the eraser?



Throw a ball several times and observe its path carefully. Describe how it moves. Make a rough sketch of the ball's path.

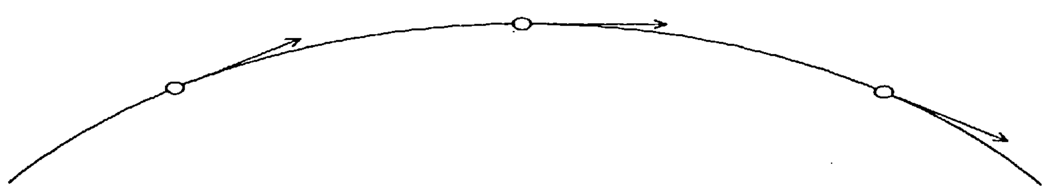


Look at the diagram below showing the flight path of a ball. The ball is shown at two positions. In each position an arrow represents the forward motion of the ball. Think of the arrows as showing the speed of the ball and the direction it was moving at each instant.



As it flew through the air, the ball did not move along the dotted straight line at a steady speed. Instead, it moved in a curved path. Its direction kept changing. What force was acting on the ball to change its motion? Not friction. At low speed, friction with the air has very little effect on the ball.

What other force could be acting on the ball? Can you draw arrows to show the force acting on the ball?



There are no strings attached to objects moving in space. A man-made satellite is not tied to the earth like a whirling rock on a string. No giant hawser pulls on the moon, keeping it in a curved path. Yet the moon travels in orbit around the earth. The earth orbits the sun. These objects have great mass. Why do they travel a curved path? Shouldn't they tend to continue moving in a straight line at constant speed?

You know that when a force is applied, the motion of an object changes. Some force must be pulling on the ball you threw to curve it toward the ground. Force must be acting on the moon to keep it from moving in a straight line. Force must be affecting the motion of the earth to keep it in a curving track around the sun.

Long ago people would simply have said that it is natural for a ball to fall to the ground when it is thrown. It was thought perfectly natural for the moon to move in orbit around the earth. But now we can think of these motions as being caused by a force. You can't see this force, yet you know it is there, acting on the ball and on the moon as if they were tied to the earth. This force is *gravitation.*

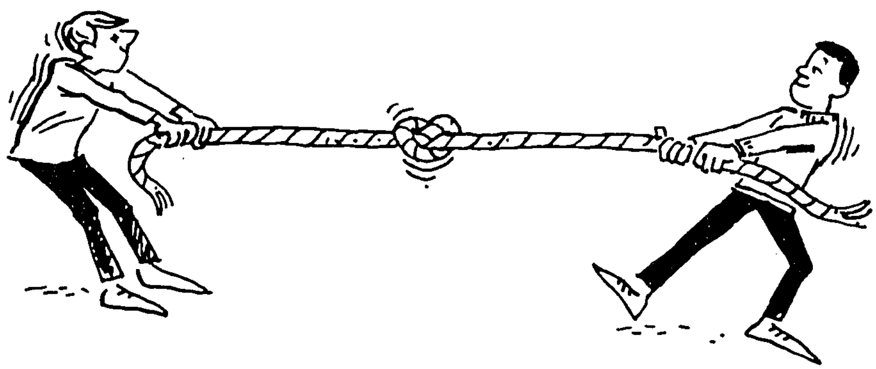
In what ways does the force of gravitation affect the motions of objects? How does gravitation cause the ball to follow a curved path back to earth? Why does the moon keep moving in orbit century after century? Let's find out more about how objects change their motions when forces are acting on them.

CHAPTER 4

Forces and Speed

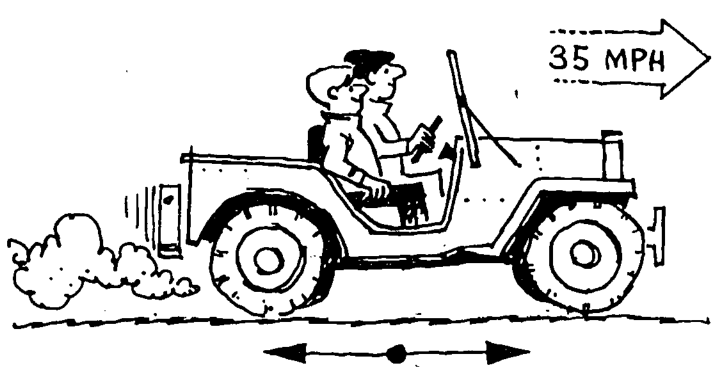
Tug a knotted rope in one direction and have a partner pull just as hard in the opposite direction. Which way does the knot move? Can you explain why?

When two forces are equal in strength but act in opposite directions, the forces are *balanced*. The resulting force, the *net force*, is zero. The knot in the rope remains stationary.

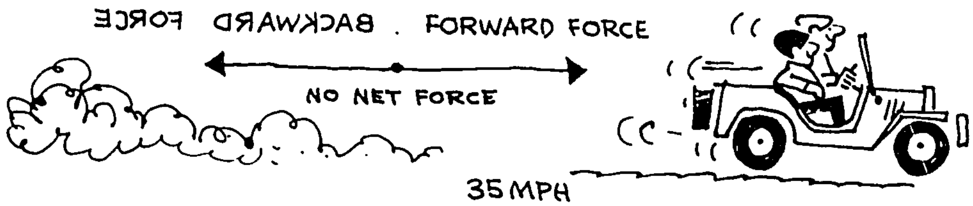


Can balanced forces also act on a moving object?

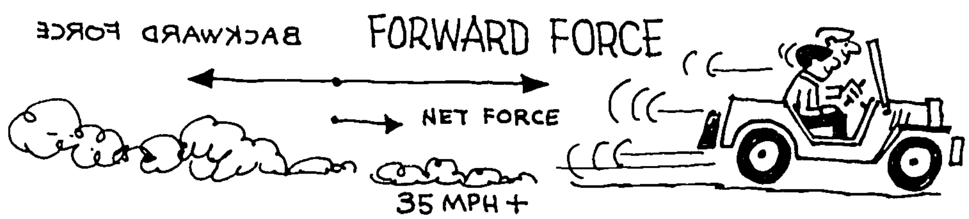
Imagine you are riding in a jeep on a straight stretch of road. Not another car is in sight. The jeep is moving along at a constant speed of 35 miles an hour. It is neither gaining nor losing speed. Picture the forces acting on the car. There is the force driving it forward, and also the backward force of friction. Think of these two forces being equal, but acting in opposite directions. The forces are balanced. The result, the net force on the jeep, is zero. So the jeep moves along at constant speed.



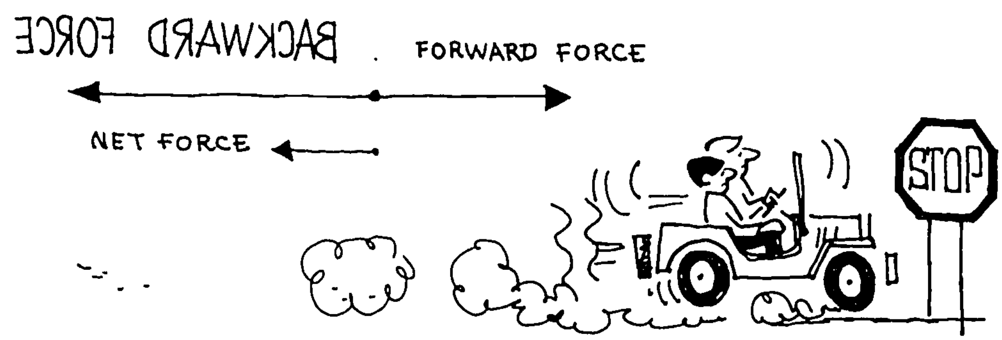
Step on the gas pedal. What happens? A net force acts on the jeep. It acts on you too, and you feel the push. The forward force is now greater than the backward frictional forces, and the forces on the jeep are no



longer balanced. A net force is pushing in the direction of the jeep's motion, so you gain speed in the direction you are going. Soon you are traveling at 45 miles an hour.



Let up a little on the gas, and the jeep moves at a steady speed again. It rolls along at 45 miles an hour. Once again the forward force is balancing the backward frictional force. The net force is zero. Speed is constant.



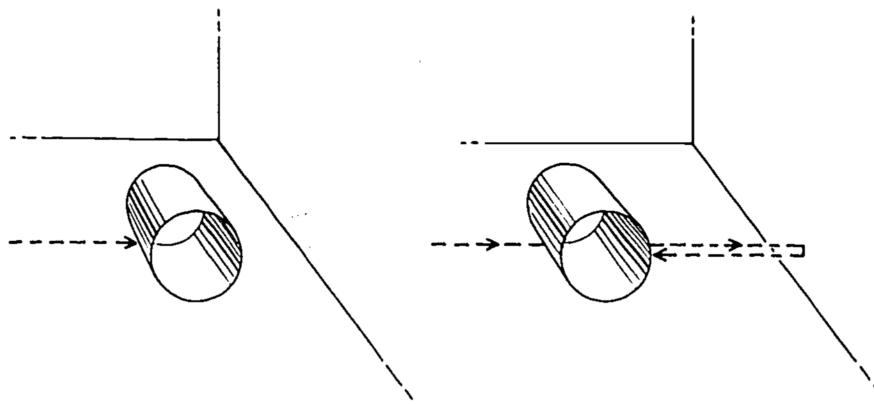
Stop sign ahead! Step on the brake and the frictional forces become much greater. The forces are unbalanced again. In which direction is the net force acting? What happens to the jeep's motion?

FORCE AND MOTION

You don't have to ride in a jeep to understand how force affects the motions of objects. You can work in the classroom.

Stand about 8 feet from the wall of your classroom. Place an empty can on the floor. Then give it a push so it rolls toward the wall. Watch what happens to the can the instant it strikes the wall.

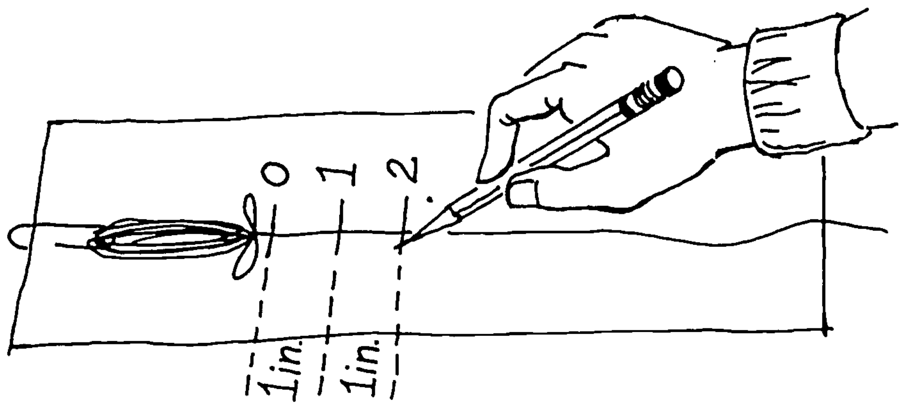
Picture the forces at work in your experiment. When the can was motionless on the floor, there was no net force acting on it. The can stayed just where it was. But the instant you gave it a push a net force acted on it. Which way did the force act? Which way did the can move? Did you have to keep pushing the can in order to maintain its motion?



If you watched the can roll toward the wall, you probably noticed that it moved at almost constant speed. As it rolled, there was practically no net force acting on the can. So it just kept moving along steadily in a straight line. What happened to the can when it struck the wall? In which direction was the net force applied? What happened to the motion of the can?

In the world of moving things we occasionally see a quick push or pull. But most forces act on objects for a longer time. Let's see what happens to an object when a *constant* force continues acting on it for a while.

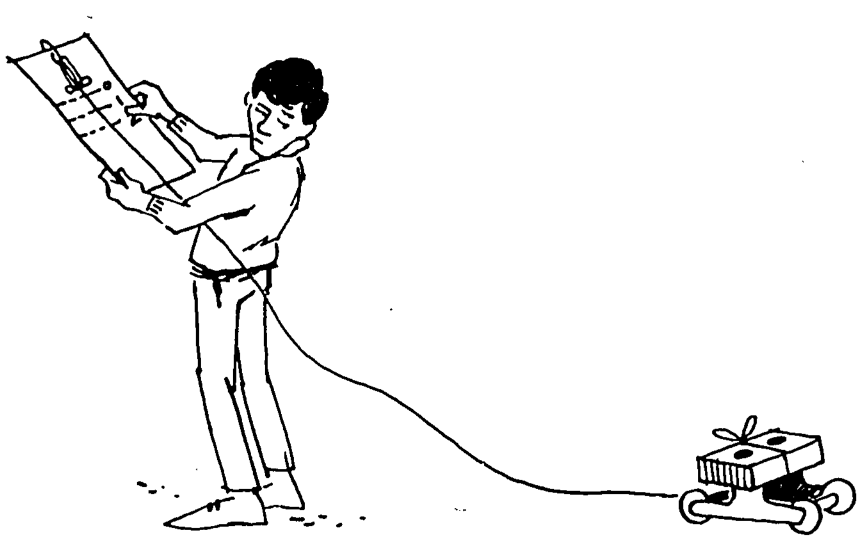
Make a rubber-band scale to measure force. Place a paper clip at the edge of a thick piece of cardboard. Slip two rubber bands through the clip. Each rubber band should measure about 3 inches in length. Use rubber bands that are of the same thickness. Tie a 5-foot piece of string to the rubber bands.



Hold your scale so the string and rubber bands hang toward the floor. Make a mark beside the bottom of the rubber bands. Make two or three more marks at 1-inch intervals below the first mark.

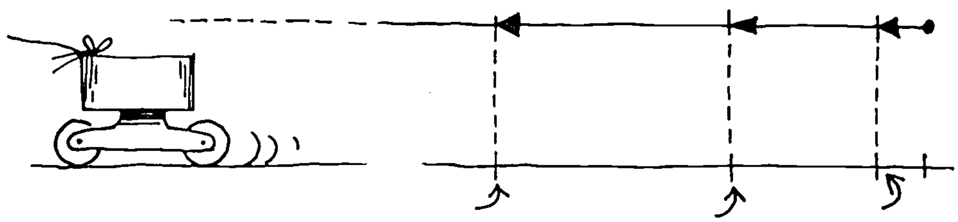
Now tie the other end of the string to a small cart with a brick in it. Place the cart and its load on the floor at one end of a long hallway. Holding the rubber-band scale with both hands, take a position ahead of the cart. Make sure that the string is not too loose.

When you are ready, pull the loaded cart with the rubber-band scale. Try to keep the force steady. Practice until you are satisfied you can do it well. Keep the end of the rubber bands at mark No. 1 on the scale. In this way you will be pulling with a constant net force of mark No. 1. What happens to the speed of the cart? What must you do to keep pulling with a constant force?



Try this activity several times. How fast is the cart moving when you first start to pull it? Notice the speed after you've been pulling with a *constant* force for one second; then for several seconds. The arrows in the sketch represent the distances traveled by the cart in each unit of time.

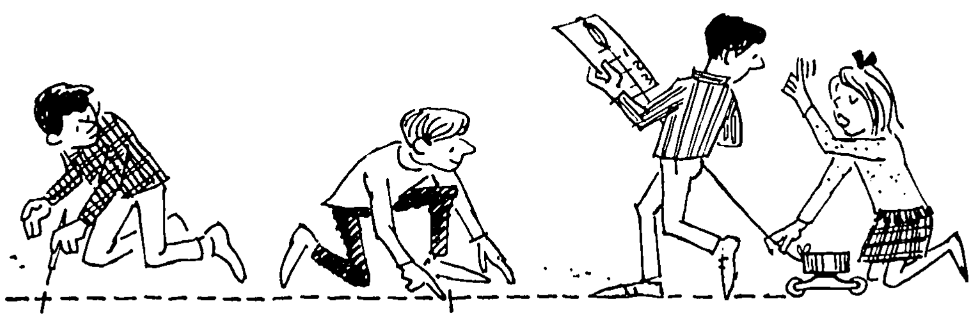
Can you see that the cart is constantly changing its motion? It is being accelerated. What is happening to its speed during each second? Can you imagine how fast it would be traveling after 10 seconds?



MEASURING ACCELERATION

In the last activity you applied a constant force to the loaded cart. You found that the cart continued to gain speed, that is, to *accelerate*. So a constant force seems to make an object keep changing its speed, keep accelerating. Let's see if acceleration can be measured.

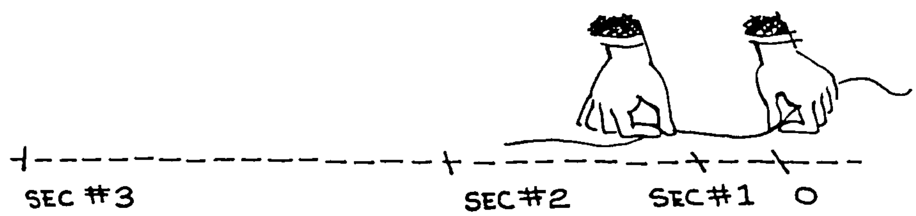
Use the loaded cart and the scale again. Place a marker on the floor beside the front wheel. This will show the cart's starting point. Use the force scale to pull the cart just as you did before. Try your best to keep the rubber band at mark 1 on the scale so the net force on the cart will be constant. In this activity keep track of time in seconds.



It may be difficult to keep the force constant and make precise measurements of time. Practice before trying this activity. When you are confident that everything is ready, start the cart moving with a force of mark 1. Keep the force constant.

At the end of second No. 1, have an observer put a mark on the floor to show the position of the front wheel of the moving cart. Have other observers do the same at the end of seconds No. 2, No. 3, and No. 4. They will have to work quickly.

Let's try to estimate the acceleration of the cart. Stretch a string from the "start" mark to the position of the cart at the end of second No. 1. See the illustration. Call this length one *unit* of distance. Now find out how many of these units the cart traveled from the end of second No. 1 to the end of second No. 2.



How far does it move in the next second? The next? Make a record of your measurements. Don't be too concerned if the distances come out in fractions. Simply round off all measurements to the nearest whole number and enter in a table like the one at the top of page 27.

To find the acceleration of the cart, arrange the data in your copy of the table. Enter the measurements from your activity in the middle column. At the end of second No. 1, how far has the cart traveled? One unit of distance. It moves one distance unit in one second. So its speed was 1 unit/sec. Read this quantity as "one unit per second." How far did it move in the next second? What was the speed? Its speed was 3 units/sec. The cart traveled two distance units farther in this second than in second No. 1. You can say the cart speeded up 2 units/sec during this second. When the cart speeds up, it is accelerating. So its acceleration was 2 units/sec in a second.

Remember that the constant force of mark 1 was acting on the cart. Look at your table on the following page. What do you notice about the speed of the cart from one second to the next second? Complete the acceleration column. What do you notice about the acceleration of the cart at different times?

Time from Start	Distance Traveled Each Second (average speed)	Increase in Speed in One Second (acceleration)
0 sec.		
	1 unit/sec.	
1 sec.		2 units/sec. each second
	3 units/sec.	
2 sec.		units/sec. each second
	units/sec.	
3 sec.		units/sec. each second
	units/sec.	
4 sec.		

You worked as carefully as possible to find data on the cart's motion. But no matter how hard you tried, some errors probably occurred. What are some reasons for errors in measurement? Why was it so difficult to measure accurately?

If precise measurements of time and distance could be made and the net force on the cart were constant, your table would look something like the one below. Notice that each second the cart travels a greater distance than the second before. So each second the average speed of the cart is increasing.

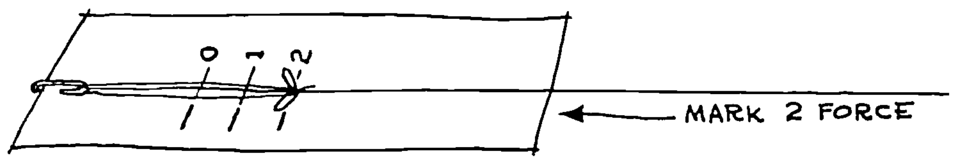
What was the acceleration of the cart? With a constant net force of mark 1, the cart gains speed at the same rate every second. The acceleration is constant—2 units/sec each second. A *constant force* seems to result in *constant acceleration.* Did you find similar results?

Time from Start	Distance Traveled Each Second (average speed)	Increase in Speed in One Second (acceleration)
0 sec.		
	1 unit/sec.	
1 sec.		2 units/sec. each second
	3 units/sec.	
2 sec.		2 units/sec. each second
	5 units/sec.	
3 sec.		2 units/sec. each second
	7 units/sec.	
4 sec.		

FORCES AND ACCELERATIONS

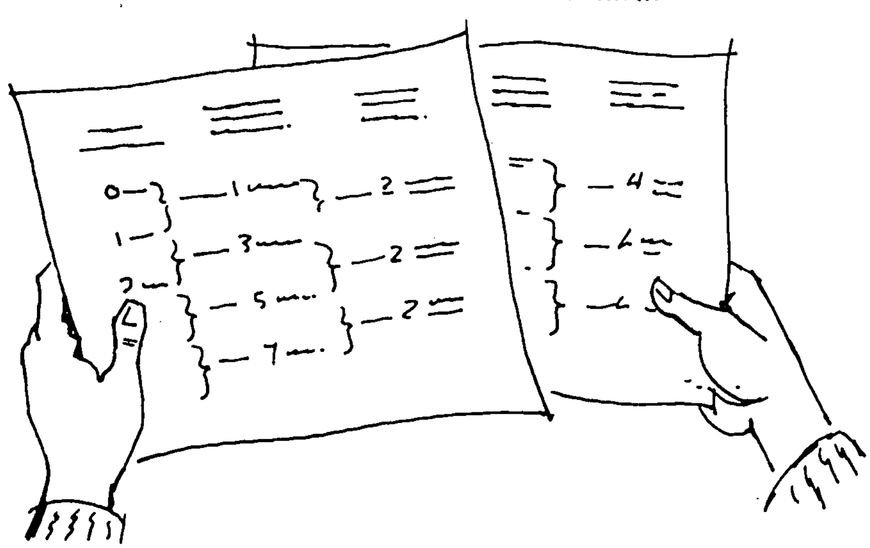
You have observed the cart as it was accelerated by the constant force of mark 1. What will happen to the cart if the load remains the same, but the net force on the cart is greater? Can you guess something about the rate of acceleration? Test your hunch.

Work your experiment in exactly the same manner as before. This time, however, exert more force. Pull the cart with the rubber bands stretched to mark 2. It may be difficult, but try to keep the force constant all the time.



Use the same distance unit as in the first experiment. Make measurements as you did before. Forget about fractions and simply round off all distance measurements to the nearest whole number. Then enter the data in a new table to find the acceleration of the cart when the force is mark 2.

Compare your acceleration data with those from the first experiment. Make comparisons of your findings for each second. How do the accelerations compare? From the results of this experiment, can you make a statement that tells how force affects acceleration?



In this experiment, as in the one before, measurement errors creep in. If you had been able to make precise measurements of time and distance when the net force on the cart was doubled, your table would contain the data shown below.

Time from Start	*Distance Traveled Each Second (average speed)*	*Increase in Speed in One Second (acceleration)*
0 sec.		
	2 unit/sec.	
1 sec.		4 units/sec. each second
	6 units/sec.	
2 sec.		4 units/sec. each second
	10 units/sec.	
3 sec.		4 units/sec. each second
	14 units/sec.	
4 sec.		

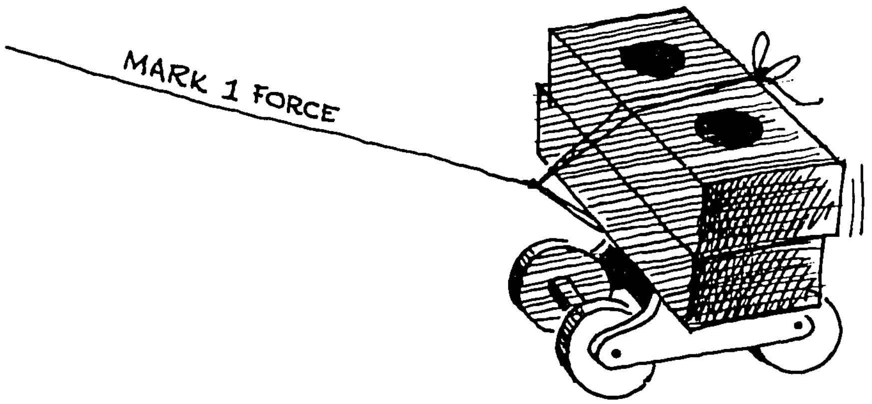
Remember the load is the same but the force was doubled. What happened to the acceleration when the force was doubled? Can you make a rule about force and acceleration?

The tables can be used to find a quick clue to the acceleration. Take a moment to compare the distance traveled in second No. 1 with the rate of acceleration. What do you notice? Now look back to the table at the bottom of page 27 and make the same kind of comparison. Can you find the relationship between the distance traveled in second No. 1 and the rate of acceleration?

ACCELERATION AND MASS

Suppose you repeat the experiment. This time, however, keep the force at mark 1 but double the mass. How will the acceleration be affected? Make a good guess and then experiment to find out if your guess is reasonable.

Place a second brick on top of the first and tie them both to the cart. Now the mass of the object is almost doubled. Accelerate this mass with the force of mark 1. Try to keep the force constant. Make distance measurements with the same unit you used in previous activities. Again, remember that you will not be able to make precise measurements. You will merely round off all distances to the nearest whole numbers.



With the mass doubled, what do you notice about the speed of the cart? How much distance does it move during each second?

Make a new table and find the acceleration of the cart when the mass is doubled. Compare your data with the data from the activity just completed. Make comparisons of your findings for each second. How do the accelerations compare? Can you make a statement that tells how acceleration is affected by mass?

If precise measurements of time and distance were made when the mass of the cart was doubled, your table should contain data shown below.

Time from Start	*Distance Traveled Each Second (average speed)*	*Increase in Speed in One Second (acceleration)*
0 sec.		
	½ unit/sec.	
1 sec.		1 unit/sec. each second
	1½ units/sec.	
2 sec.		1 unit/sec. each second
	2½ units/sec.	
3 sec.		1 unit/sec. each second
	3½ units/sec.	
4 sec.		

In this activity the force remained at mark 1, but the mass was doubled. What happened to the acceleration? As mass increases, how is acceleration affected? Can you explain why? Try to invent a rule that tells how acceleration is related to mass.

Compare the distance traveled in second No. 1 to the rate of acceleration. Do you notice the same relationship you discovered before?

FORCE, MASS, AND ACCELERATION

Now let's put together the two rules you invented. Each tells something about how objects accelerate.

From your experiments you learned that when force increases, acceleration increases. Do away with friction, make precise measurements of forces and distances, and keep the mass constant. You find that when force is doubled, acceleration is doubled. If force is tripled, acceleration is three times as great. Look at the table on the left, below. Notice what happens to acceleration when force is 500 times as great. The acceleration of any object is *directly* related to the force exerted on it.

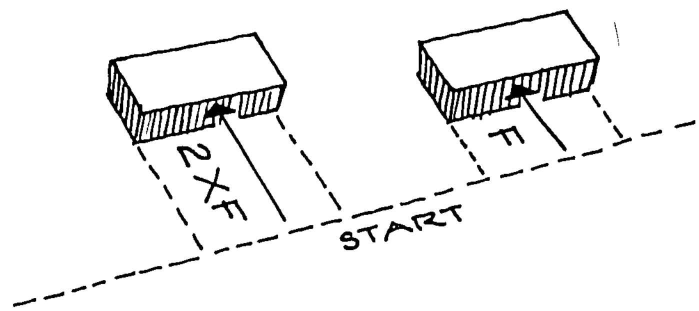
Force	*Acceleration*
1	1
2	2
3	3
500	500

Mass	*Acceleration*
1	1
2	$\frac{1}{2}$
3	$\frac{1}{3}$
100,000	$\frac{1}{100,000}$

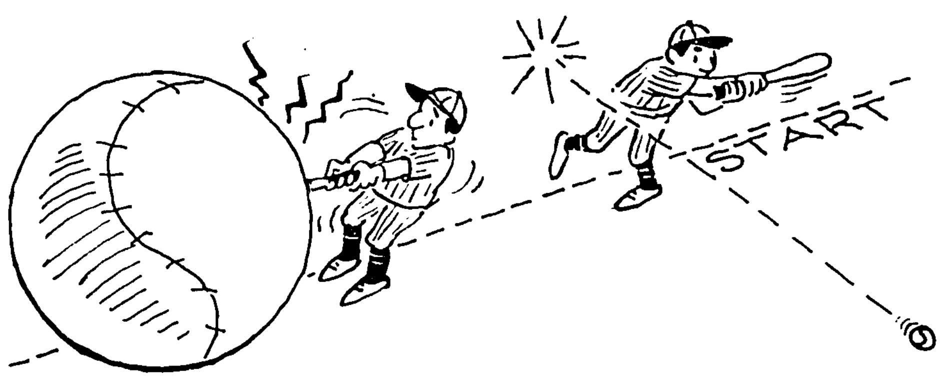
You have also learned that when mass increases, acceleration decreases. Keep the force constant and accelerate objects. Under ideal conditions you find that when mass is doubled, acceleration is halved. If mass is tripled, acceleration is just one-third as great. What happens when mass is raised to 100,000? In each case, notice in the table on the right, above, that the acceleration number is the *inverse* of the mass. The acceleration of any object is *inversely* related to its mass.

From your experiments with forces and masses you found two relationships that tell about the acceleration of objects. Long ago Isaac Newton put these same rules together in one statement, which we call a law of motion. Newton stated that the acceleration of an object depends *directly* on the net force exerted on it and *inversely* on the mass of the object.

Think of two objects of the same mass. Exert twice the force on one as on the other and its acceleration will be twice as great. Think of an object with a small mass and another a million times as massive. Push each with the same force. The more massive body is accelerated only one millionth as much.



Try this problem. Imagine there is no friction and all your measures are precise. Think about the acceleration if you double the mass and also double the force. How will the acceleration be affected?



What will happen if both force and mass are 100 times as great? A million times as great? Can you see what would happen if the force and mass are multiplied by the same number? Would the acceleration change?

In this chapter you have learned that an object accelerates when a force acts on it. And you have seen that the acceleration is in the direction of the net force. You have found that the acceleration of an object is directly related to the force exerted and inversely related to the mass of the object. And when force and mass are increased in the same proportion, the acceleration is unchanged.

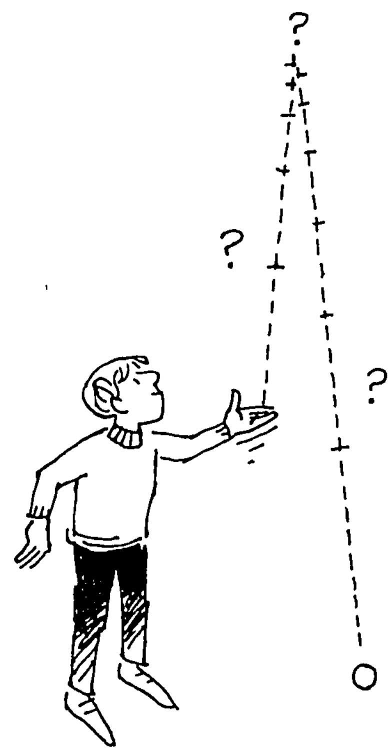
Although your experiments have been with a loaded cart, perhaps you have already guessed that these same rules work for any object pushed or pulled on earth. How are objects accelerated when they are not touching the ground but are being pulled toward the earth by the force of gravitation? Do falling objects obey Newton's law of motion?

CHAPTER 5

Gravity Around the World

You have seen how different forces affect the motions of objects. Astronomers are very much concerned with one particular force—gravitation. When they talk about gravitation and its effects at and near the surface of a celestial body, they speak of *gravity*. How does gravity accelerate objects near the earth?

Throw a ball upward. As it moves upward, does it travel at constant speed? What is its speed at the top of its flight?

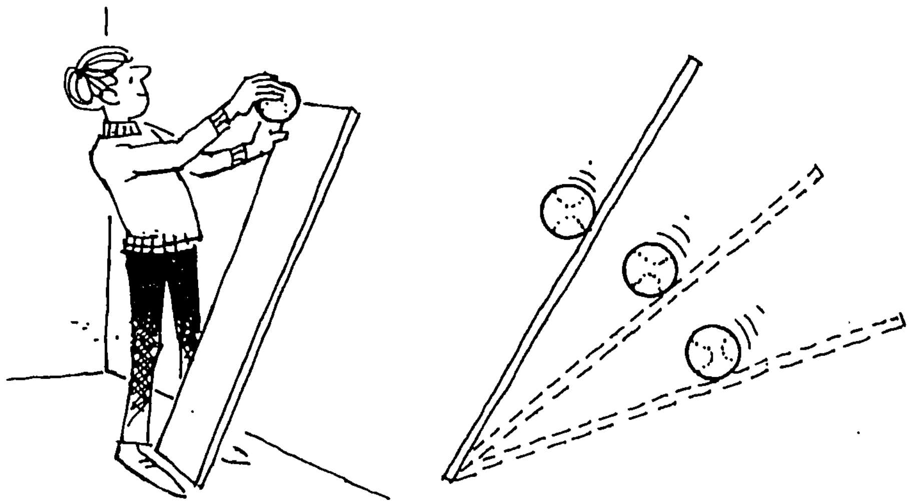


On its upward journey the ball changes speed. You have learned that any object tends to continue moving in a straight line at constant speed unless a force acts on the object. When a force is applied, the object's motion is changed. Any change in speed—faster *or* slower—is an acceleration. So in its upward path the ball is accelerated. In which direction is the force acting? On the downward journey the ball is also accelerated. In which direction is the force pulling?

Your experiments with the truck showed you that if you exert a constant force, an object moves with a constant acceleration. How about gravity near the surface of the earth? Does this force produce a constant acceleration downward? To find out, we can put gravity to work on a falling object and observe how the object moves. We can measure the object's acceleration and see if it remains constant.

It's not easy to measure the acceleration produced by the earth's gravity because balls and books fall very rapidly. There isn't much time to measure. But Galileo solved this difficult problem in a simple way. He reasoned that a ramp gave him a chance to study effects of gravity more easily.

Prop a smooth straight board against the wall so the board makes a ramp that is almost straight up and down. From a position near the



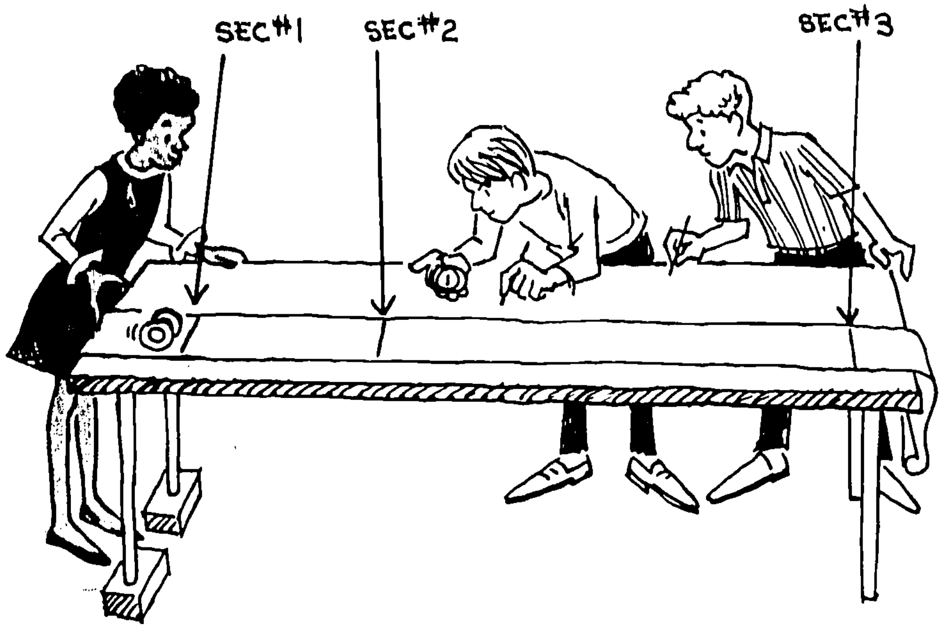
top of the ramp, drop a ball so it falls freely to the floor. Does it seem to accelerate on its downward path? Now, from a similar height, release a ball so it rolls down the steep ramp. Does it seem to accelerate as much? Make the ramp less steep by pulling the bottom away from the wall. Roll the ball again and observe its speed down the ramp.

Try rolling the ball up the ramp. Is its acceleration similar to that of a ball thrown upward in the air? Continue to make the slope of the ramp less and less, each time rolling the ball upward and downward on the ramp. What happens to the acceleration as the ramp becomes less steep?

The acceleration of a ball is less when it is on a ramp than when it is falling freely. But you know, as Galileo believed, that gravity provides the downward force in both cases.

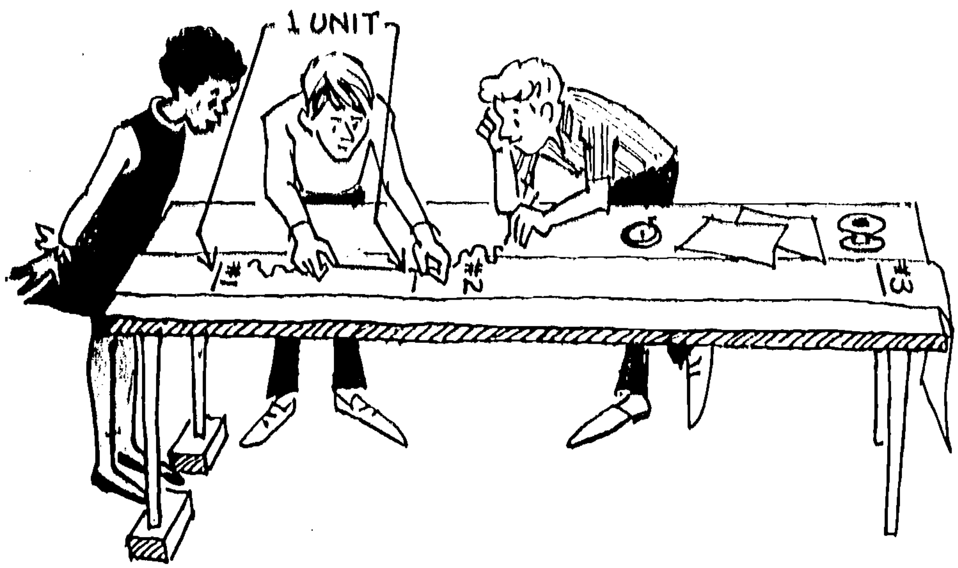
GRAVITY AND ACCELERATION

With a ramp that has a gentle slope like the one below, you can make some measurements that will help you discover how the earth's gravity accelerates objects.



Make a ramp by placing blocks of wood under two legs of a long smooth table as shown. Roll an empty adhesive-tape spool down the ramp and time it. Adjust the slope of the ramp so that the spool takes at least three seconds to roll the length of the table. Tape a long strip of paper along one side of the table. Near the very top of this strip, make a mark for a starting position. Place the spool at this point. Release the spool and measure how far it rolls in exactly one second. Repeat this activity several times to find the average distance for one second. Using the same procedure, find the average distance for second No. 2 and second No. 3. Make all your marks on the paper strip.

Stretch a string from the starting place to the average mark for the first second. Call this length one unit of distance.



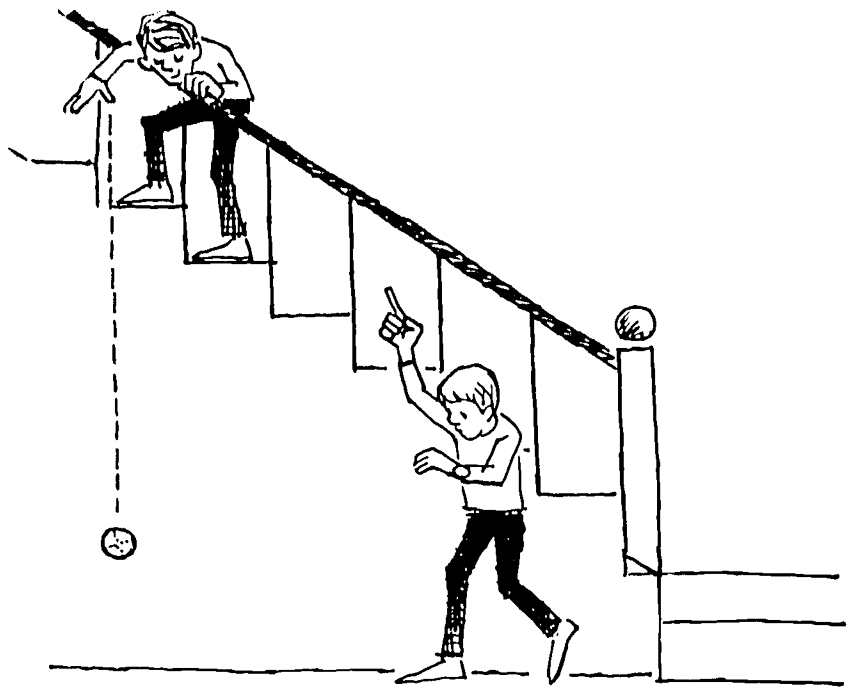
How far did the spool travel in second No. 2? In second No. 3? Organize your data in a table, similar to the one below, just as you did in Chapter 4. Find the acceleration.

You know the speed changes from second to second. Do you also find a change in acceleration? Notice how far the spool rolled in second No. 1. Look at the acceleration. How is the acceleration of the spool related to the distance traveled in second No. 1?

You have seen how the earth's gravity accelerates a spool rolling down a gentle ramp. But the distance traveled by a rolling spool in second No. 1 is one thing; the distance traveled in the same time by a free-falling body is another. Let's find how gravity accelerates a free-falling body.

Time from Start	*Distance Traveled Each Second (average speed)*	*Increase in Speed in One Second (acceleration)*
0 sec.		
	unit/sec.	
1 sec.		units/sec. each second
	units/sec.	
2 sec.		units/sec. each second
	units/sec.	
3 sec.		

Drop a ball down a stairwell from different heights. Have an observer record time in seconds. From one position the time of fall may be less than one second; from a higher step it may be more. Find the height from which the ball takes exactly one second to fall to the floor. Measure time as precisely as possible. Measure the distance carefully. One way might be to use a long string with a weight at the bottom.



What distance did the ball fall during second No. 1? You know that this distance is related to the rate of acceleration. Now what can you say is the rate of acceleration of the falling ball?

BIG STUFF, LITTLE STUFF, AND GRAVITY

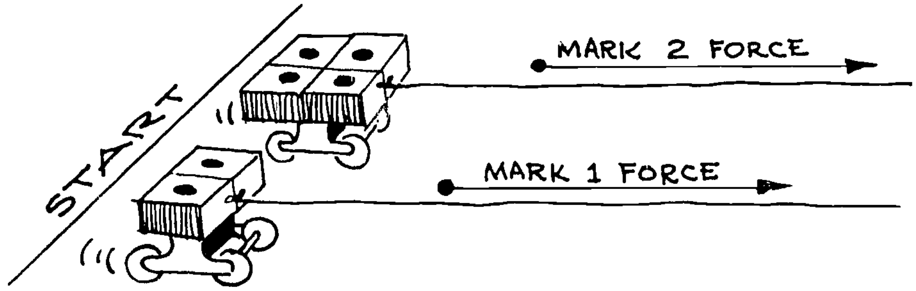
Now recall the cart experiments in Chapter 4. When you exerted a certain force, you found that the cart with a two-brick mass accelerated at a rate only one-half that of the one-brick mass. Other things being equal, the acceleration of any object depends inversely on its own mass. Does this rule work for free-falling bodies? Does gravity accelerate objects in this same way?

Find two small boxes the same size. Put sand into one box until it is half full. Fill the other box all the way. One box will have twice the mass of the other. Tape each box closed so that no sand spills out. Now stand on a high chair and prepare to drop both boxes at the same instant. At what height do you hold each box so that both will land at the same time? Try it. Did you find what you expected? Try it again. Hold each box so both will land at the same time.

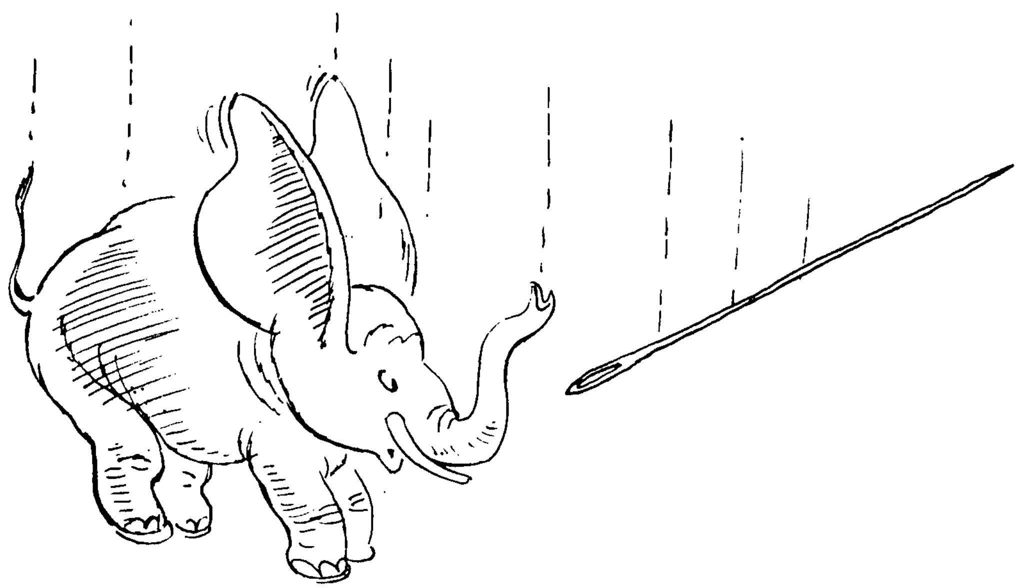
Remember to drop them at the same instant. Does the amount of material in the boxes have anything to do with how each box is accelerated by gravity?

Drop an elephant and a needle together in a vacuum so there is no air resistance. The elephant is two million times as massive as the needle. The elephant keeps his eye on the needle, and the needle keeps its eye on the elephant. Who sees what as they fall? Do they see eye to eye?

Recall the loaded carts. You could have achieved the same acceleration for two bricks as you did for one. What amount of force would you have to exert on the doubled mass so that it would be accelerated at the same rate as a single mass?



The force of gravity causes the elephant to fall at the same rate as the needle. So the acceleration of the elephant and the needle are the same. But the elephant's mass is two million times the needle's mass. How can the massive elephant be accelerated at the same rate as the needle? The only conclusion we can make is that the gravitational force on the elephant must be two million times as great as the gravitational force on the needle.

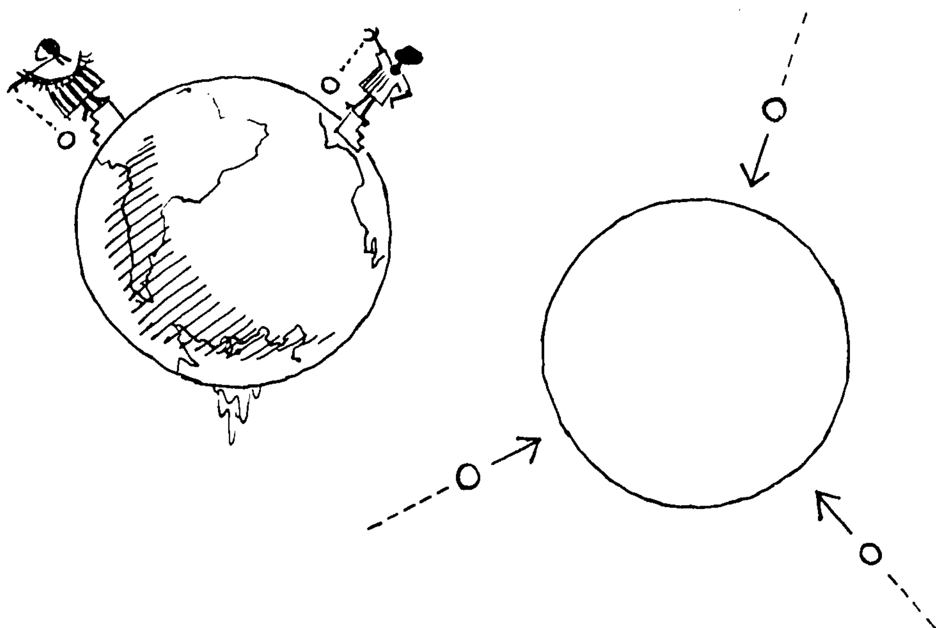


Whatever else may be true for gravity at and near the earth's surface, the *force* of gravity depends directly on the mass of the object being pulled. But the *acceleration* of any object by gravitational force is the same—no matter what the object's mass. Elephant and needle fall downward at the same rate. Their acceleration is constant. Their speeds increase by 32 ft/sec each second.

TOWARD THE CENTER

Next let's look around the world. Suppose a boy in Liberia drops a ball down a stairwell to find the distance fallen in one second. Will he get the same result you did? Suppose a girl in Chile tries the same experiments. What acceleration number will she find?

The circle below is drawn to represent the earth. The arrows show the force of gravity pulling on a falling ball in three places around the earth. Use straight lines to extend the force arrows on a tracing of the drawing until they intersect. Where do they meet?



It would seem that something at the very center of the earth exerts a force on objects near the surface. Perhaps you would say that it is the matter of the earth. But not all the matter of the earth is at the center—4000 miles below us. The material of the earth is spread out in the form of a huge sphere. You live on the surface of this sphere.

Isaac Newton went to great trouble to satisfy himself that the gravitational force exerted by a sphere of matter on any outside object is exactly the same as if all the matter in the sphere were squeezed together to a point at the very center.

So wherever you are, on or near the surface of the earth, the force is always directed downward—toward the center of the earth. And the acceleration of gravity is practically 32 ft/sec each second toward the center.

Here's a puzzle. Can you imagine where the acceleration of gravity might be less? Can you guess why?

CHAPTER 6

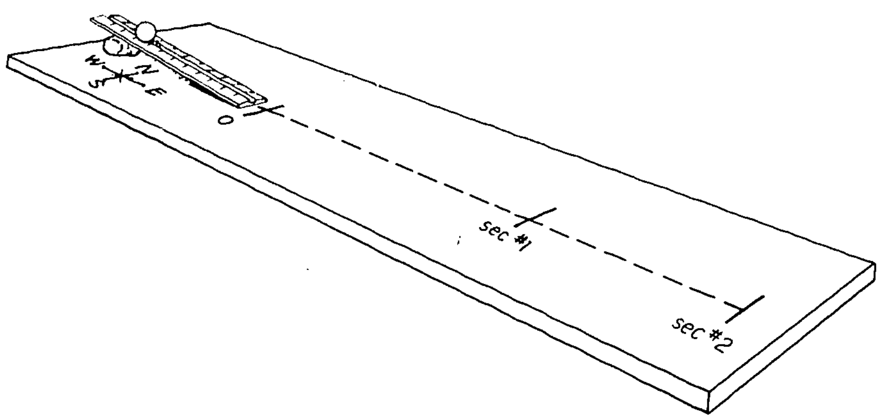
Bumps, Curves, and the Moon

You have seen how gravity works near the surface of the earth. You know too that somehow the gravitational force of the earth rules the motions of objects far from the earth's surface. Man-made satellites go around the earth. The moon orbits around the earth once a month.

In order to understand more clearly how gravitational force affects the motion of a distant object like the moon in its orbit, let's first find out how straight-line motion may be changed.

Find a ruler with a groove along its length. At one end of a long smooth table, prop up one end of the ruler to form a ramp with a gentle slope. Keep the ramp in a fixed position by packing clay at the sides. Place a marble near the top of the groove. Let the marble roll. The instant after the marble leaves the ramp, measure its motion for exactly two seconds. Place a mark where you start the timing.

Place another mark where the marble is one second later, then where it is a second after that. You should have three marks on the table.



If the table is very smooth and level with the floor, and if you timed precisely, your marks should be evenly spaced in a straight line.

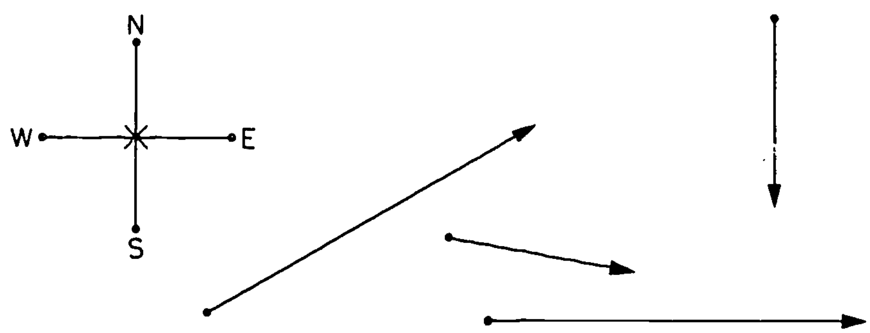
Roll the marble several times. Start from the same point on the ramp. Do the best you can to measure time precisely.

Use a yardstick to find the average distance traveled in each second. Compare the speed for each second. Do you find much of a difference?

Perhaps your marble moved due east at a speed of 2 ft/sec. You can make an arrow diagram to represent the motion of the marble.

Choose a convenient scale to represent speed. For example, suppose you decide that one inch represents a speed of 1 ft/sec. How long should your arrow be to indicate the speed of the marble at 2 ft/sec? What way was the marble moving? In what direction should you draw your arrow?

Look at the diagram below. Which arrow best represents the motion of your marble in a second? Can you explain why?



The arrow tells two things about the marble's motion. It shows the *speed* of the marble, 2 ft/sec. It also indicates the *direction* the marble is moving—east.

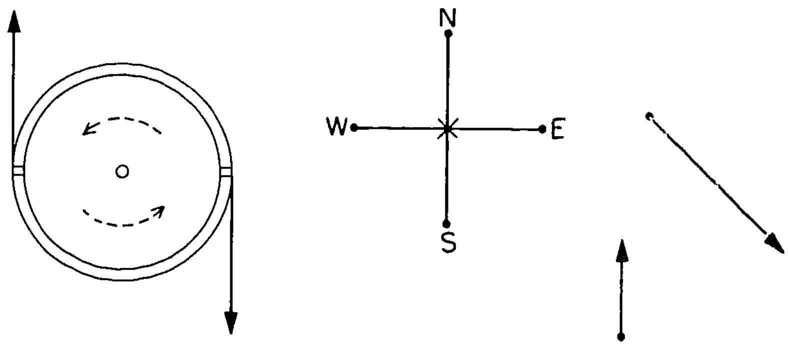
When arrows are used in this way, they are called *vectors*. You can always extract two bits of information from a vector—amount and direction. The *length* of a vector may show the strength of a force or the speed of an object. The *direction* of a vector may show the direction that a force is acting or an object is moving. At this time, you will be working with vectors that show speed and direction. Such vectors represent *velocity*.

Velocity is something like speed, but not exactly. Two pupils run away from a telephone pole at the same *speed*. Will they arrive at the same place at the same time? Not necessarily. What if one runs east and the other runs north?

Now suppose the same pupils run away from the telephone pole at the same *velocity*. Will they arrive at the same place at the same time?

Turn a wagon or a bicycle upside down and stick a bit of white adhesive tape onto one of the tires. Now spin the wheel slowly and watch the tape. The tape moves in a circle at a certain speed, maybe 5 mi/hr. The *speed* stays the same for a while, but the *direction* of motion is changing all the time. At one moment, the tape is moving upward at 5 mi/hr. Half a turn later it is moving downward at 5 mi/hr.

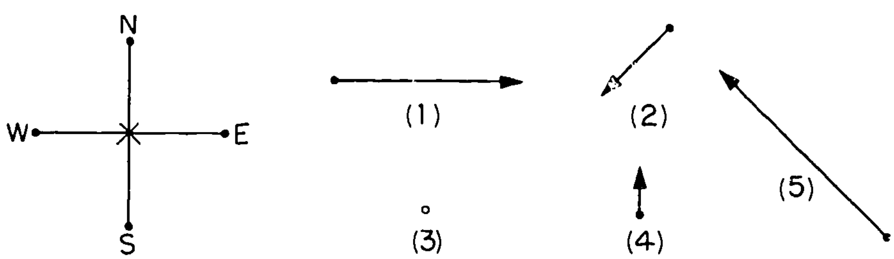
If you are going to describe the velocity of the tape, you must tell both its speed *and* direction at that time. Its speed is constant, but the direction always changes, so the velocity of the tape is constantly changing.



Think of the wind. One afternoon it may be blowing 10 mi/hr toward the north; the next afternoon, 25 mi/hr toward the southeast. Each of these quantities is a velocity vector. You can draw a velocity vector for any moving object by laying your ruler in the correct direction and then measuring off the speed on whatever scale you choose.

Practice using vectors by trying these examples:

1. The vectors below have been drawn to a scale of ½ inch to 10 miles an hour. Use a ruler to find the speed. Then read the velocity of each vector.

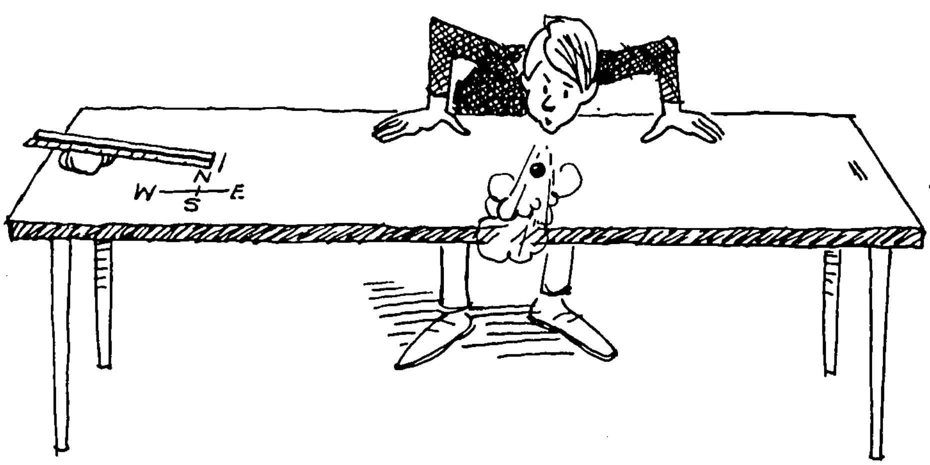


2. Using the same scale and directions as above, draw velocity vectors for the following quantities: (a) 40 mi/hr south; (b) 30 mi/hr southwest; (c) 60 mi/hr northeast.

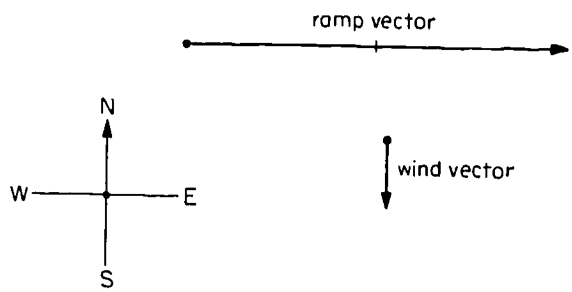
3. Select your own scale. Draw a velocity vector to show your motion from your seat to the pencil sharpener if you make a 15-foot beeline trip in 5 seconds. Does your vector show speed and direction?
4. A turtle and a rabbit start a race together. They both run in the same direction. Stop the race. The rabbit has run 50 times the speed of the turtle. Draw velocity vectors to show the motion of both animals. Use a convenient scale for your vectors.

On page 44 you made a velocity vector to represent the speed of the marble and the direction in which it moved. While the marble was moving on the table its velocity was practically constant. Can you explain why?

Put the marble in motion again, but do it another way. Place the marble at the middle marker on the table. Have a partner stand at the side of the table, facing the middle marker. On signal he blows a quick, sharp blast of air against the marble. Keep time as in the previous activity. Place a marker at the marble's position at the end of the first second. Do the same at the end of second No. 2. You will make better measurements if you try several times. Find the average of the distance moved in each second. Draw a vector of the velocity of the marble. Use the same scale you did with the ramp: 1 inch represents a speed of 1 ft/sec.

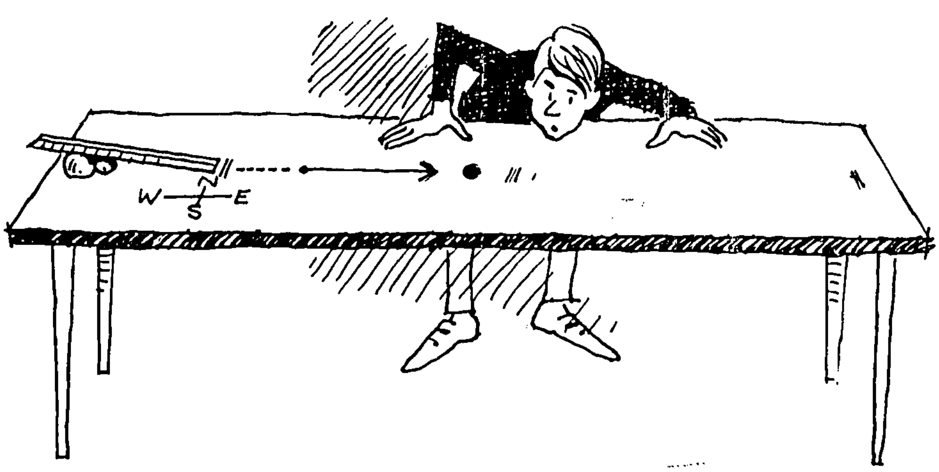


Transfer the velocity vectors of the marble from each activity to a sheet of paper. Examine each vector. Compare the speeds of the marble in each activity. Compare the directions. Can you make a comparison of the size and direction of the net force that made the marble move along the table in each activity? Remember that a marble, or any object, will be accelerated in the direction of a net force.



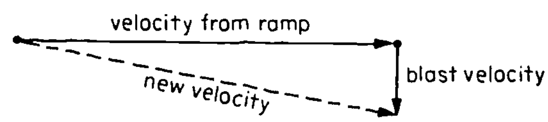
A net force caused the marble to change velocity each time. Let's find out what will happen to the marble when you combine velocities.

Now for some teamwork. Ask your partner to stand next to the middle marker. Roll the marble down the ramp exactly as before. Keep time carefully. Just as the marble passes the middle marker, your partner should blow as hard as before against the rolling marble. He would have to practice to time the air blast just right. Notice the position of the marble 1 second after the blow. Place a marker at this position. Repeat this activity several times to find the average position of the marble 1 second after it was blown.



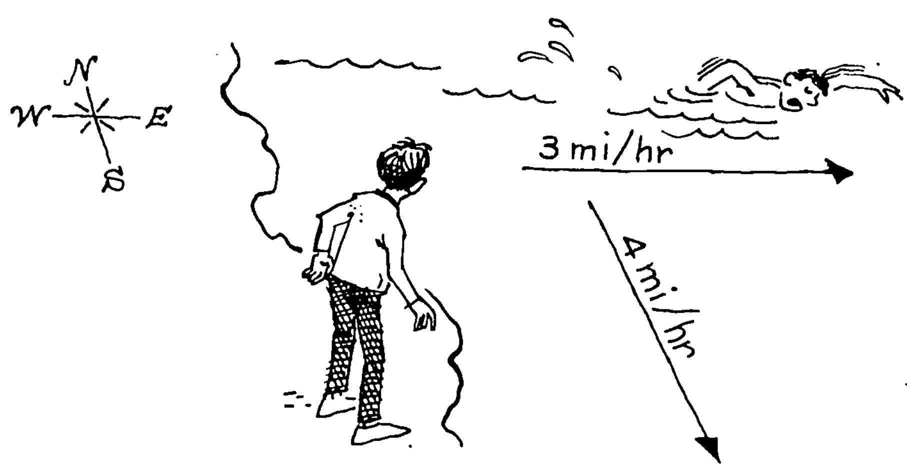
Draw a new velocity vector to represent the motion of the marble during the last second. Is this new vector like either of the old vectors? Why did the marble change velocity? Look at the diagram at the top of page 48 to see what happens when velocities are combined.

One vector describes the velocity of the marble as it rolls from the ramp across the table. The other vector describes the velocity of the marble after it is blown from a position at rest. When these two velocities are combined, the direction of the marble is changed and it has a different velocity. And when the velocity of an object changes, it has been accelerated. If the marble is accelerated, a net force must have been exerted on it. Look at the vector diagram. Notice the vector for the new velocity, particulary its direction. Try to make a reasonable guess about the direction of the net force that accelerated the rolling marble.



You already know that when an object changes speed it is accelerated. Now you also find that when a marble changes direction it is accelerated. These two ideas can be combined into one statement. When an object is accelerated, its *velocity* changes. It moves at a new velocity—at a different speed, or in a different direction, or both.

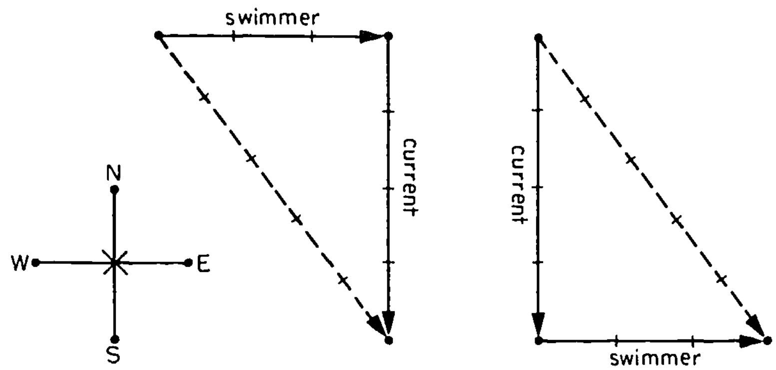
When your friend blew, the marble was accelerated to a certain southward velocity. When that velocity was combined with the original velocity from the ramp, the marble was accelerated. And it moved with a new velocity.



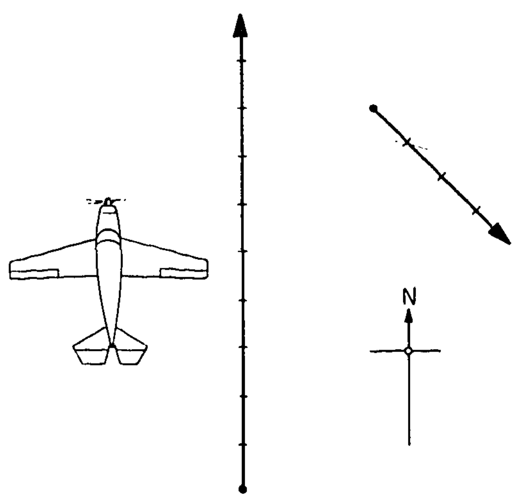
A swimmer wants to cross the Mississippi River from Iowa to Illinois. He dives in and swims eastward at 3 mi/hr. Notice this velocity vector in the diagram above. But the river is flowing south at 4 mi/hr. Notice this vector, too. What is his velocity as seen from the shore?

You can find the answer by putting the tail of either vector at the tip of the other one, as you see in the diagrams.

The *length* of the dotted line that completes the triangle gives the speed of the swimmer. Its *direction* shows the direction of his progress as seen by anybody on the shore. He moves with a velocity of 5 mi/hr in a generally southeast direction, landing downstream.

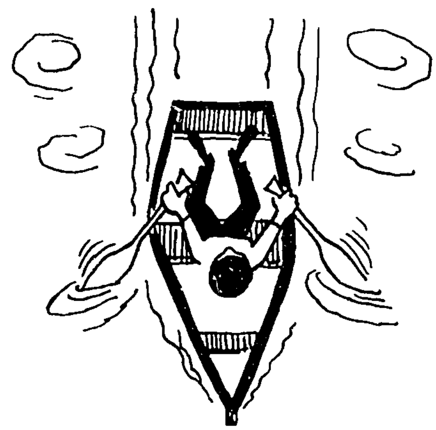


Try these two problems with pencil, ruler, and paper. Set up your compass directions and make a convenient scale for speed.



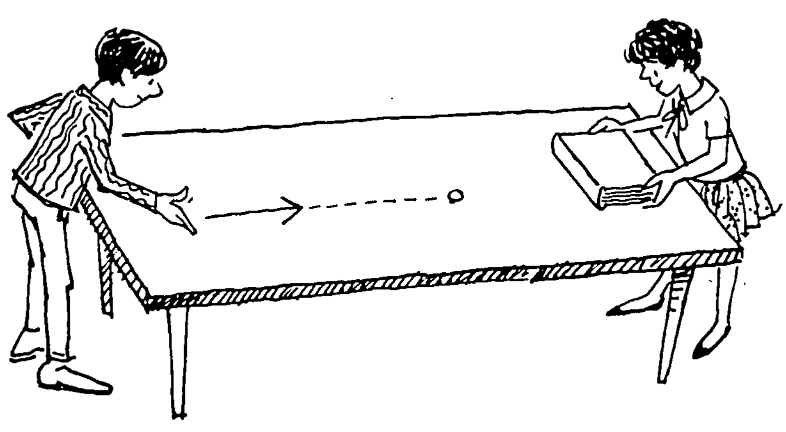
1. A plane flies north with an air speed of 100 mi/hr, but the wind is blowing toward the southeast at 40 mi/hr. Make one vector showing the velocity of the airplane northward. Make another vector showing wind velocity. Put the tail of the wind vector to the tip of the airplane's vector. What is the speed of the plane over the ground?

2. A man rows a boat south at 3 mi/hr through a current that is flowing west at 3 mi/hr. How fast is he moving over the river bottom and in what direction?



Probably you had little trouble finding the direction of the velocity vector of the swimmer, the plane, and the boat. But if it was difficult to describe the direction of the net force that changed the velocity of the marble, don't be a bit surprised. The net force worked for only a fraction of a second—too quickly for you to notice. The following activity will help you find the direction of a net force which results in a certain change in velocity.

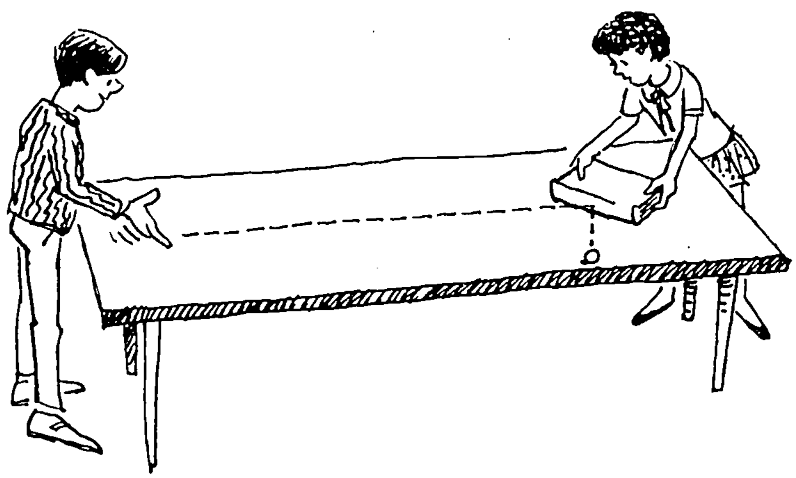
Place a book at one end of a smooth table. Have a friend roll a marble along the table straight toward the book. Just as the marble is about to hit, give it a slight whack with the edge of the book. Try



to bounce the marble so it rolls straight back to your partner at the same speed he rolled it toward you. Try this activity several times until you have the ball rolling each way at about the same speed.

In this activity the marble changed velocity when it struck the book. It was accelerated when a force was applied. In which direction was the book moved? In which direction was the force acting on the marble?

Try the activity once again. Your friend rolls the marble just as he did before. But this time you do not shoot the marble back to him. Instead, you give the marble a slight whack so that it travels off at right angles to the old path. Find the best position and move your book so you get the angle just right. Try to keep the speeds the same.

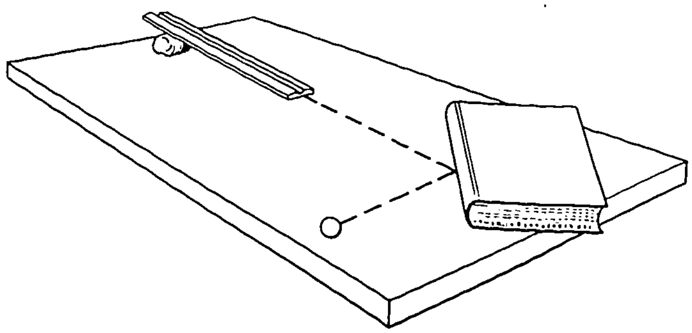


Once again you are accelerating the marble. In which direction did you move the book? In which direction is the force acting this time?

To find the exact direction of the force that accelerated the marble, make a record of the marble's track.

Place a large sheet of black construction paper on the floor or on a large table. Place a book in the middle of the sheet of paper at the proper angle. This time the book is stationary. Set up a ramp as shown on page 52. Make the ramp fairly steep and fix it in position with clay. Roll a steel ball or a heavy marble in some talcum powder. Let it roll down the ramp. The marble will leave a powder trail on the paper, recording its track before and after the collision with the book.

On the black paper, mark a chalk line along the edge of the book where the marble has bounced off. Remove the book and you see a track of the marble's motion before and after it struck the book. And by using vectors you can find the direction of the net force that causes a change in velocity.



Call the marble's path before collision the *old* velocity and the path after collision the *new* velocity. Assume that the marble loses no speed due to the collision. Suppose the marble travels at the speed of 1 ft/sec before and after collision. Place a dot to show the marble moving along the old velocity line one foot before the collision point. Do the same along the new velocity line one foot after the collision point. Make arrows to show the velocity vectors. So in two seconds the marble moves with its old velocity, collides with the book, and moves off with a new velocity.

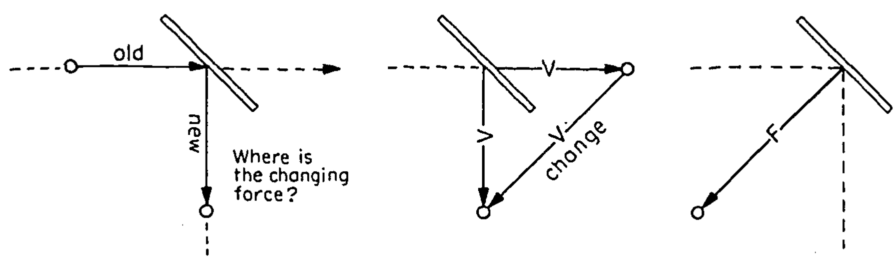
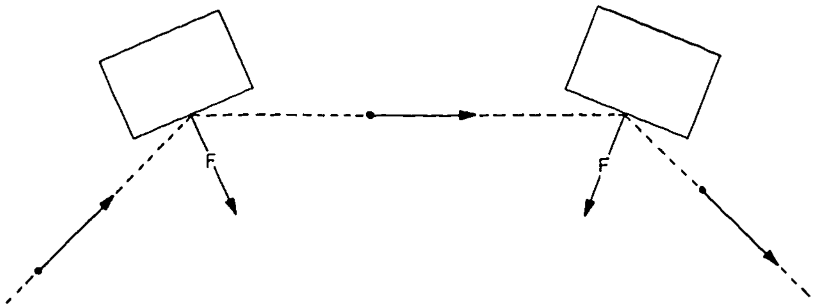


Fig. 1 Fig. 2 Fig. 3

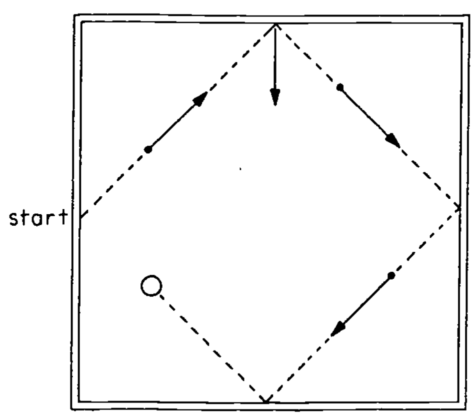
If the book were not in the way, the marble would have continued moving at the old velocity. One second later it would have been in a position at the tip of the dotted arrow above. But at the instant the marble did hit the book, it was accelerated. The marble moved with a new velocity. You know that the acceleration was due to a force from the collision with the book. With your vector diagram, you can find the direction of the force that accelerated the marble to a new velocity. Simply draw a straight line from where the marble would have been without the book to where it actually was one second after collision. This line tells something about the change of velocity that resulted in the new velocity of the marble. It also tells you about the direction of the net force exerted on the marble at the point of collision.

Try the same activity as the previous one, but use two books. Arrange them so the marble will bounce off the first book and hit the second one. Experiment until you get the marble to roll in the manner shown below. When you are ready, dust your marble and let it roll.



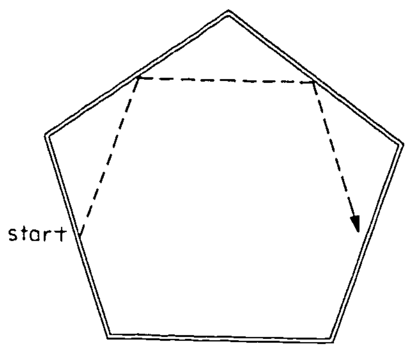
Mark the edge of each book. Try making force arrows as you did before. Notice the direction of the force each time the marble collides with a book. And each time a force is applied, the marble is accelerated. It rolls along a new path.

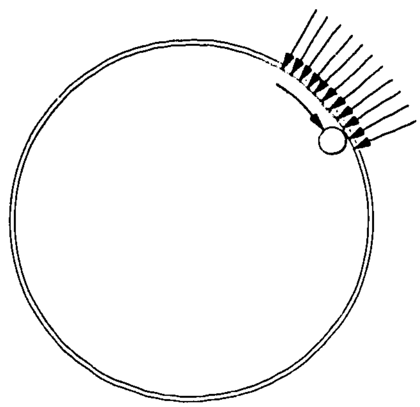
Most people have watched a billiard ball bounce off the side cushion of a billiard table. Picture a square billiard table, as in the diagram below.



Imagine that the table is extremely smooth so that friction will not slow the ball for a long time. Now shoot from the center of any side toward the center of an adjacent side. The dotted line shows the first trip of the ball around the table. Notice the velocity of the ball after each collision. What are the directions of the forces that accelerate the ball at each collision? Think of your experiments with the book and the marble. Where do all the force arrows point?

Next, imagine shooting the ball on a billiard table of five equal sides. Shoot from the center of any one side to hit the center of the next side. Draw a diagram with your own force arrows to explain the acceleration of the ball. Where do all the force arrows point? Notice the angle between the cushion and the ball's path. Is the angle the same as on a square table?



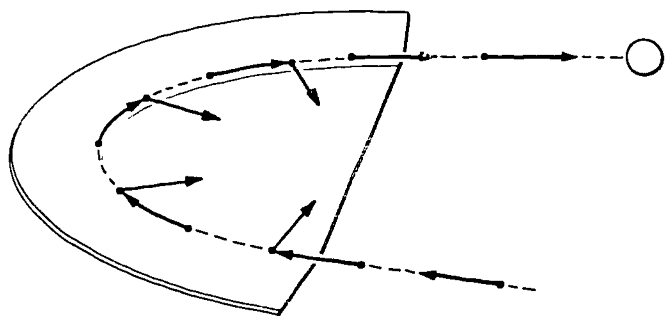


Now imagine trying the same thing on a billiard table with a hundred equal sides. Shoot from the center of one side to the center of the next side. This time the distance between impacts is rather small, and so is the angle between cushion and track. The ball makes 100 collisions each go-around. What about the change of velocity and force at each impact? Where do the force arrows point?

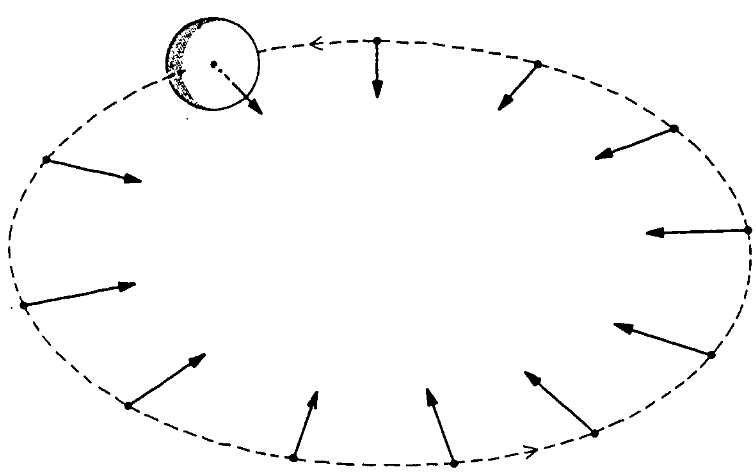
Imagine a table with a million equal sides. What happens? The shape of the table is almost circular: the impacts of the ball are very frequent.

Finally, think of a perfectly circular table. The ball is touching the cushion continuously. The angle between cushion and track is zero. What is the path of the ball as it moves around in its track? What is the direction of the force being exerted by the cushion on the ball? In which direction is the ball being accelerated?

You can make a model of part of a circular billiard table by cutting a paper plate in half. Roll a marble toward the plate so that it travels around the rim. The track is straight before and after. But when the marble is in contact with the rim, what can you say about its velocity vector? About its acceleration? About the force on it?



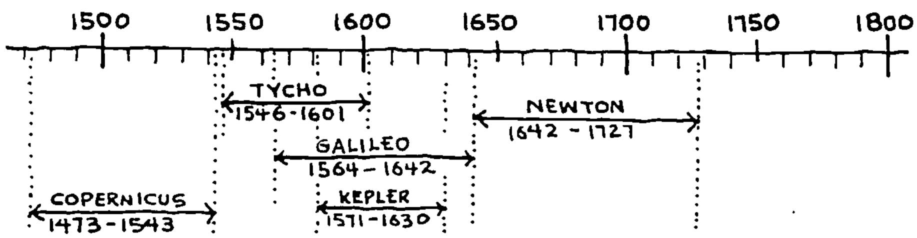
The moon goes around the earth in an orbit that is nearly circular. Let us imagine that it is circular. The moon is not tied to the earth with a celestial chain, nor is it rolling around the rim of a huge pie plate. Yet it continues to move around month after month in its orbit, responding to a constant pull. From your experiments with the books and billiard tables, you have learned about the direction of a force that causes objects to move in a constantly changing path. If you were to draw many, many force arrows to explain the acceleration of the moon, where would all these arrows come together? And at the center of the circle, what do you find exerting a pulling force on the moon—yesterday, tomorrow, and in a hundred million years?



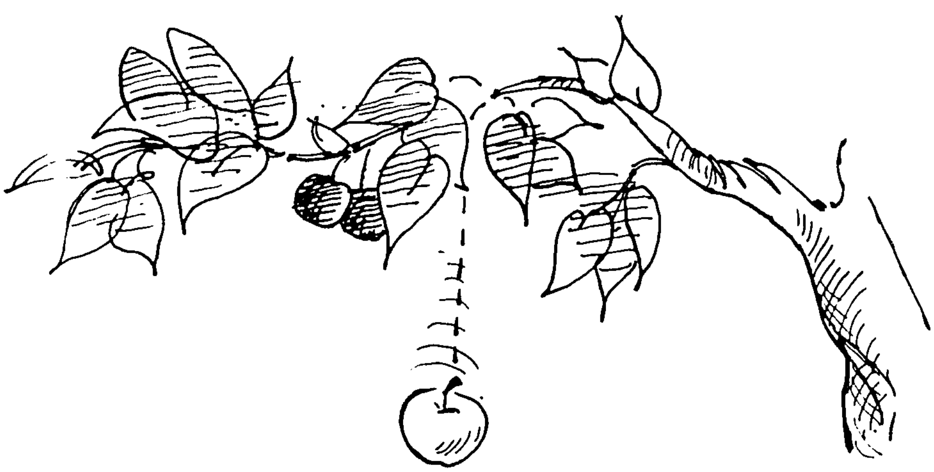
CHAPTER 7

Newton and Gravitation

Isaac Newton was born in England in 1642, a year after Galileo's death and twelve years after the death of Johannes Kepler (yoe-HAHN-ess KEP-ler). Galileo had studied motions of objects here on earth; Kepler discovered three laws that described how planets move. One of Newton's particular interests was to follow up the work of Galileo and Kepler, who described *how* objects move here on earth and out among the planets. Newton went further and answered the question of *why* things move the way they do.



A story is told that Newton, in a thoughtful mood one day, watched an apple fall from a tree in the orchard near his home in Woolsthorpe-by-Colsterworth. Watching the apple fall, Newton wondered if the force pulling the apple was also at work far from the earth.



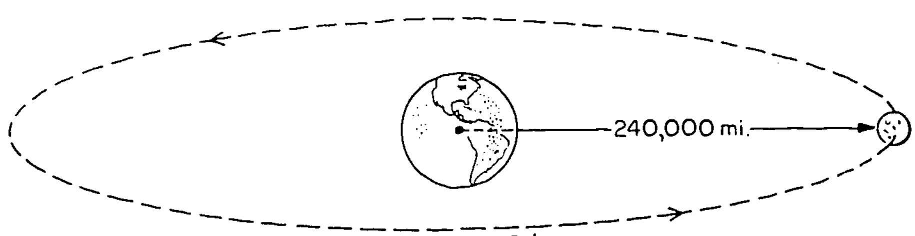
MOON AROUND THE EARTH

From the work of Galileo and other scientists, Newton knew that the acceleration of the apple, or of any freely falling object near the earth's surface, was 32 ft/sec each second toward the center of the earth.

He knew that the moon was being accelerated toward the earth as it moved in a nearly circular orbit—once around every month. And this acceleration had to be caused by some force from the earth, pulling the moon continuously toward the earth. Newton was confident that this force was gravitation, that it was indeed the same force that brought the apple to the ground.

But is the pulling force as strong at the moon's great distance as it is here on the surface of the earth? Perhaps it is stronger out there; or perhaps weaker. Let's find the acceleration of the moon in its orbit as Newton did. When we are finished, we can compare the acceleration of the moon with the acceleration of an object near the surface of the earth —32 ft/sec each second.

The first task is to figure out how fast the moon is traveling along its orbit. The orbit is nearly circular, and the average distance from earth's center to moon's center is 240,000 miles.



When you know the radius of the orbit, you can calculate the circumference. Work it out for yourself.

$$C = 2 \times \pi \times R$$
$$C = 2 \times 3.14 \times 240{,}000$$

Your answer will be in miles.

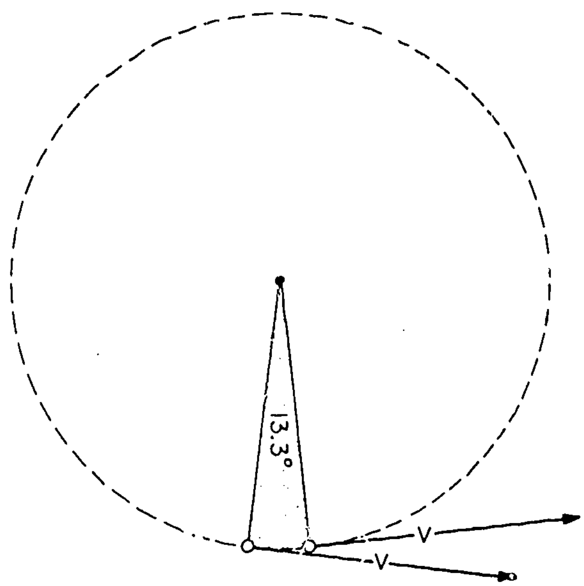
The moon takes about 27 days to complete one orbit. How far does the moon travel in this time? Now figure out the moon's speed in miles per day.

A more convenient way to describe the moon's speed is in feet per second. If you changed the unit of measure from miles per day to feet per second, you would find that the speed of the moon is approximately 3400 ft/sec.

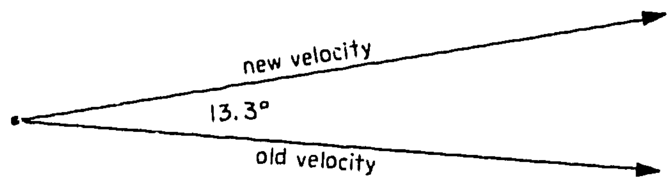
The next task is to find how much the gravitational force of the earth pulls the moon from a straight-line path. It takes 27 days for the moon to complete a full circle. How many degrees are in a circle? Figure out how many degrees of a circle the moon travels in a day.

Picture the moon's orbit. Dots in the illustration below show the positions of the moon at two moments exactly one day apart. An arrow represents the velocity of the moon at each position. With a vector diagram you can find the acceleration of the moon.

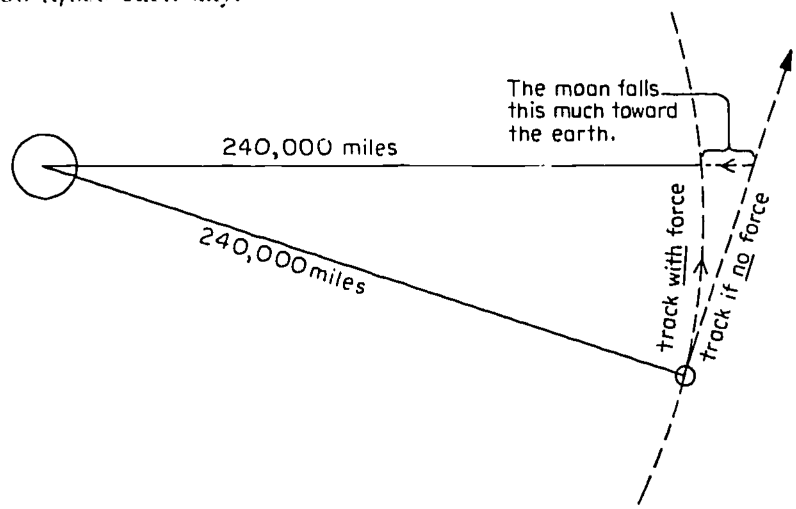
On page 59 two velocity vectors are drawn to scale. They are drawn from a common starting point. When you use vectors this way, you can estimate the *change* of velocity when the old velocity and the new velocity are known.



The moon's orbital speed is 3400 ft/sec. On the vector diagram, one inch equals 1000 ft/sec. To represent the speed of the moon each vector is 3.4 inches long. The angle between the two vectors is 13.3°. Draw the vector to represent the change of velocity. The change vector goes from the tip of the old velocity vector to the tip of the new velocity vector.



Measure the vector showing change of velocity. It is eight-tenths of an inch long, representing 800 ft/sec. Thus, the *change of velocity* of the moon is 800 ft/sec during the course of one day. This acceleration is in the direction of the earth. The moon's acceleration toward the earth is 800 ft/sec each day.



There is one more task before we can compare the apple with the moon. The apple's acceleration is 32 ft/sec each *second;* the moon's is 800 ft/sec each *day.* The units of time for apple and moon are different, so you will have to change the units for the apple to the same units you used for the moon.

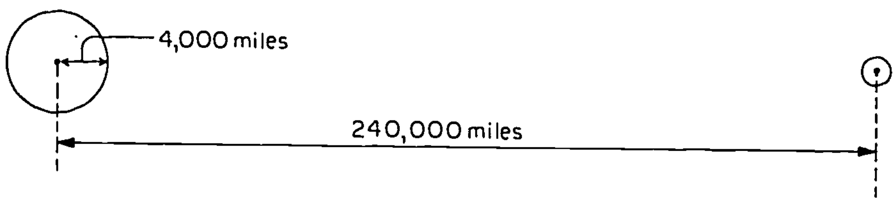
First find the number of seconds in a day. Then work out the acceleration of the apple in feet per second each day. Compare, as Newton did, the acceleration of the apple with the acceleration of the moon. How many times greater is it? Work it out.

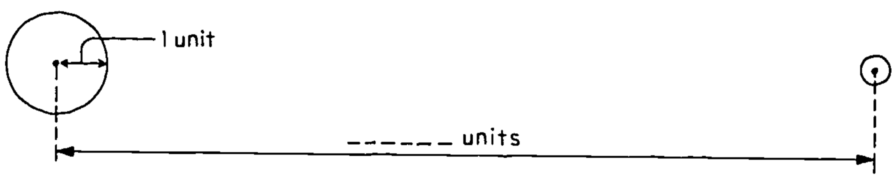
$$\frac{\text{apple's acceleration}}{\text{moon's acceleration}} = ?$$

If you could make a very accurate drawing on a large scale, and if all your measurements were precise, you would find that the acceleration of the moon is 3600 times smaller than the acceleration of the apple at the earth's surface.

Although Newton worked hard to find the acceleration of the moon, he still wasn't finished. He wanted to find a general rule to describe how the earth's gravitational pull on an object depends on the distance of the object from the earth. Compare the only two examples that Newton knew—apple and moon. How far is the apple from the earth?

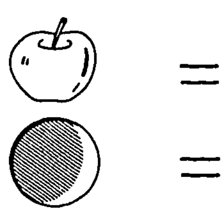
Remember that Newton worked very hard to show that the spherical earth attracts objects as if all its matter were squeezed together at the center. The diameter of the earth is about 8000 miles. How far is an apple from the center? How many times as far away is the moon from the earth's center? Look at the diagram below.





Divide the distance of the moon by the distance of the apple. Enter the number in your copy of the table below.

Look at the number you get and then compare it with the number you found when you compared the two accelerations—apple and moon. Puzzle over them until you can make a good and satisfying guess how the earth's gravitational force changes with increasing distance from the earth.



Distance	Acceleration
1	1
	$\frac{1}{3600}$

Try these problems to see if you made a reasonable guess. A space probe on the launch pad is 1 earth radius from the center of the earth. Call the earth's pull on it a force of 1 unit. Later, at various points along its orbit, the strength of the gravitational force is different. Copy and fill in the following table.

Distance from Center (miles)	*Earth Radii*	*Strength of Force (units)*
4000	1	1
8000	2	
12,000		$\frac{1}{9}$
16,000		
20,000		$\frac{1}{25}$
40,000	10	
240,000		$\frac{1}{3600}$

From your work with the table, try to make a precise statement about how the strength of the earth's gravitational force is related to distance from the center of the earth.

You have found that the earth exerts a pulling force on any object whatever—near or far away. Our studies of falling objects here on earth are local examples of something more widespread. The force of gravitation affects the motions of all objects—here at home and out in space. So motions in space are linked with motions here at home. This is a far cry from the sharp difference in motion that was believed to exist between objects on earth and objects in the sky in Aristotle's time.

PLANETS AROUND THE SUN

You know that the moon moves in orbit because a force constantly accelerates it toward the earth. And you have found how the acceleration of an object by the earth decreases with distance. Newton looked far beyond the moon and puzzled over what Kepler had learned about the motions of planets. What caused the planets to move in the way they were observed to move?

Newton had a strong hunch that a pulling force was acting on each planet, continuously accelerating it toward the sun. He wondered if perhaps the sun exerted the same kind of pull that the earth did—gravitational force. And if it did so, did the force work in the same way? Was it stronger close to the sun? Was it weaker far away?

From Kepler's work Newton knew the distances from the sun to a number of planets. He also knew the orbital periods, and so he could easily figure the speeds of the planets along their orbits. In the same way as he had done for the moon, Newton calculated the acceleration of each planet in its orbit around the sun.

Planet	*Average Distance From Sun (a.u.)*	*Acceleration (earth = 1.00)*
Mercury	0.38	6.93
Venus	0.72	1.93
Earth	1.00	1.00
Mars	1.52	0.43
Jupiter	5.20	0.03
Saturn	9.55	0.01

The table above tells the distance and acceleration of each planet known to Newton. All distances and accelerations of planets are given in units that make them easy to compare. Study the table. What do you notice about the distances and accelerations of the planets?

Let's try to find out more precisely how acceleration depends on distance.

Planet	*Distance From Sun (a.u.)*	*Acceleration (earth = 1)*
Saturn	10	$\frac{1}{100}$ ($\frac{1}{10^2}$)
Jupiter	5	$\frac{1}{25}$ ($\frac{1}{5^2}$)
Earth	1	1

Saturn's distance from the sun is roughly ten times that of the earth. But its acceleration is only about one one-hundredth as much. Jupiter is about five times as far from the sun as is the earth. What should its acceleration be?

Kepler's rules explained *how* the planets moved. Now Newton was able to show *why* they continued moving along in orbit. The planets were captives of the sun's gravitational force. This force reached invisibly out into space, controlling the motions of the planets. Indeed, if Newton's work is right, the planet *must* move in the way we observe them to do.

Gravitation works far beyond the earth. You have seen that the sun exerts the same kind of gravitational pull on planets as the earth does on an apple and on the moon. And you have found that the strength of the force is related to the *inverse square* of the distance. Gravitational attraction accounts not only for the motions of bodies in the earth's neighborhood, but also for the motions of planets around the sun.

GANYMEDE AND THE MOON

How does gravitation affect the motion of moons around other planets? The four biggest satellites of Jupiter, discovered by Galileo and known to Newton, orbit regularly around their parent planet. The largest of them is Ganymede (GAN-eh-meed); it orbits about 670,000 miles from center of Jupiter.

Look below at the table of the relative distances and accelerations of the four moons. To make comparisons a little easier, the distance of Ganymede is 1.0 unit from Jupiter and its acceleration is 1.0 unit. Callisto (kuh-LISS-toe) is about three times as far from Jupiter as is Europa (you-ROW-puh). And the acceleration of Callisto is about one-ninth that of Europa. Compare the distances and accelerations of Io (EYE-oh) and Ganymede. Does the same kind of relationship exist? Does the inverse square law seem to work for Jupiter's moons?

Satellite	*Distance*	*Acceleration*
Io	0.4	6.6
Europa	0.6	2.5
Ganymede	1.0	1.0
Callisto	1.8	0.3

Now turn to a new kind of puzzle. Compare Ganymede going around Jupiter with the moon going around the earth. Ganymede's nearly circular orbit has a radius of 670,000 miles, almost three times as far from Jupiter as our moon is from the earth. Can you make a prediction about Ganymede's acceleration toward Jupiter? Should it be as great as our moon's acceleration toward the earth? Invert the square of three and what do you get? So you may predict that Jupiter will accelerate Ganymede only one-ninth as much as the earth accelerates the moon. If Ganymede's acceleration is worked out, however, it turns out to be not one-ninth the acceleration of the moon, but 40 times as great as the acceleration of the moon.

What is wrong? Why was the prediction so far off? Does the comparison of the moon and Ganymede mean that the gravitational rules don't apply to satellites of other planets? What is the trouble? You know that Jupiter is the most massive planet in the solar system, more massive by far than the earth. Think about it.

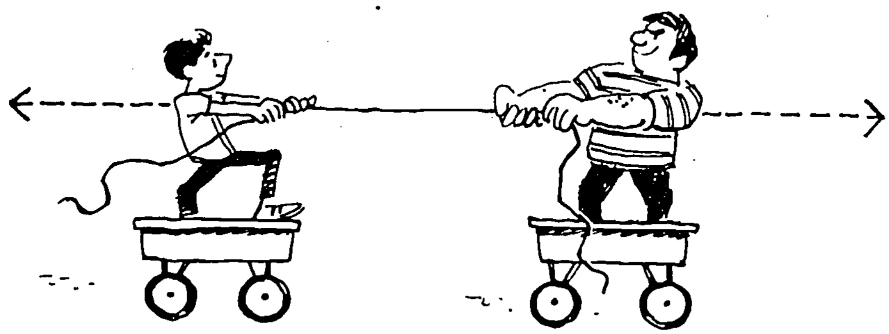
You have seen that gravitational force depends on the inverse square of the distance between two bodies. Gravitational force also depends on something else. Newton was able to account for the suprisingly great acceleration of Ganymede around Jupiter. He reasoned that the gravitational force exerted by Jupiter depended on the mass of Jupiter itself, as well as on the mass of Ganymede. In the same way, the gravitational pull by the sun on a planet depends on the mass of the sun, as well as on the mass of the planet. In fact, *any* gravitational force depends on the mass of the larger object and also on the mass of the smaller object.

Now we can put together these ideas about distance and mass to make a single statement about gravitation. The strength of the gravitational force is proportional directly to the product of the two masses and inversely to the square of the distance between them. This statement is called the law of gravitation and can be represented this way:

$$\text{force} \sim \frac{\text{mass 1} \times \text{mass 2}}{\text{distance squared}}$$

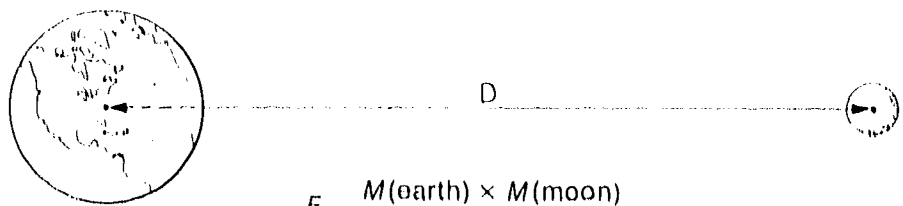
DOES GRAVITATION WORK BOTH WAYS?

Here is a puzzle. You know that the sun pulls on the earth and keeps it in orbit. But you also know that the earth pulls on the moon and keeps the moon in orbit. In any given pair, how are we to decide who is pulling on whom? Is it the more massive body that exerts the gravitational pull on the less massive body?



Think back to your statement about gravitational force. Apply it to the earth. The earth pulls on any object outside itself with a strength that depends directly on the product of the two masses and inversely on the square of the distance between them.

If the law is true, then the earth pulls not only on the moon and on apples; it also pulls on the sun. Why? Because the sun is certainly an object with mass.



$$F \qquad \frac{M(\text{earth}) \times M(\text{moon})}{D^2}$$

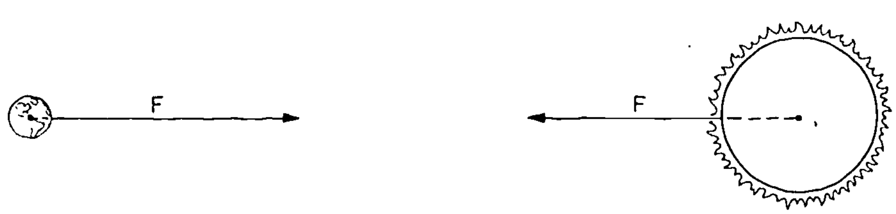
More than that, the earth pulls on the sun with the same strength that the sun pulls on the earth. First read the law of gravitation as the sun would. "I, the sun, pull on the earth with a strength that depends directly on the product of my mass and the mass of planet earth, and inversely on the square of the earth's distance from me."

$$F \sim \frac{M(\text{sun}) \times M(\text{earth})}{D^2}$$

Now read the law as the earth would. "I, the earth, pull on the sun with a strength that depends directly on the product of my mass and the mass of the sun, and inversely on the square of the sun's distance from me."

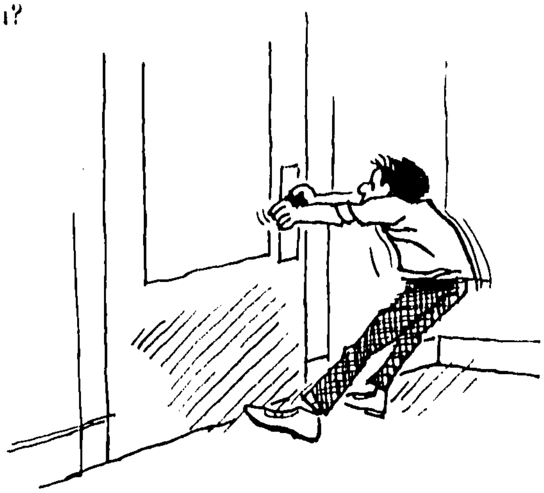
$$F \sim \frac{M(\text{earth}) \times M(\text{sun})}{D^2}$$

All three quantities that appear in both statements are identical at any one instant. So the forces are equal in strength. But they are opposite in direction. The sun pulls the earth toward the sun; the earth pulls the sun toward the earth. They pull toward each other with the same strength.



This pair of equal but opposite forces is an example of another very important rule discovered by Newton. He said that all forces come in pairs. When you push a shoe box across the floor, the box pushes backward on your hand with the same strength. And as soon as the box starts to move, the floor exerts a friction force that slows the box down. The box in turn exerts an opposite force on the floor.

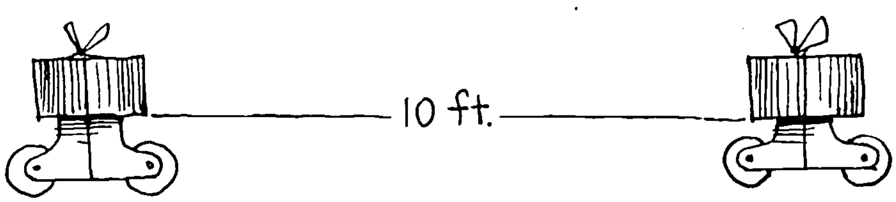
Pull with all your might on the knob of a locked door. Make sure you have a tight grip on the knob. In which direction are you exerting a force on the knob? And in which direction does the knob pull you?



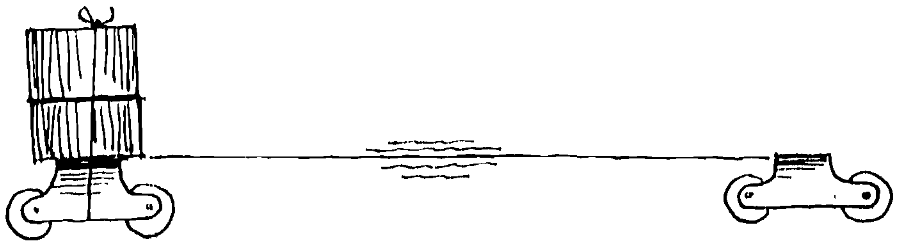
While you are pulling, another force-pair was acting on you. In which directions were each one of this pair of forces acting?

By observing force-pairs at work, you can see their effects on objects.

Attach one end of a long string of rubber bands to the front of a small cart. The string should be about 10 feet long. Attach the other end to the front of an identical cart. You and a helper separate the carts until there is a good stretch to the rubber band. Predict what will happen to both carts when they are released. At the count of three, let both go at the same instant. Watch the motions of the carts.

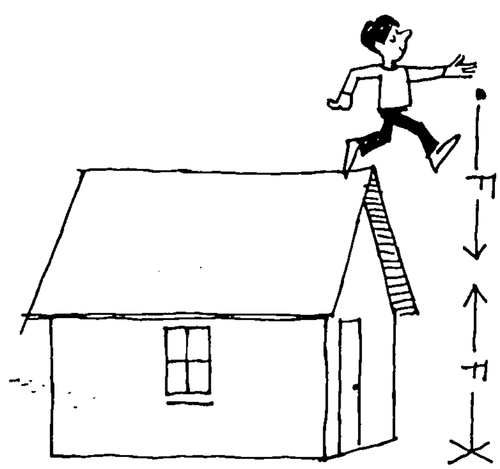


Next place equal masses in each cart. Separate the carts by the same distance as before so you keep the force the same. What will happen to the motions of the carts this time? Let go together and watch what happens.



Finally, place both masses in one cart. Leave the other empty. Repeat the activity. Notice how each cart is accelerated.

Here is what may look like an odd puzzle. Since forces always come in equal and opposite pairs, what happens if you climb out on the roof and step off? You are pulled downward by the force of gravity. But gravitational forces work both ways. The earth attracts downward, and so you must attract the earth upward with a force of the same strength. Can it be?



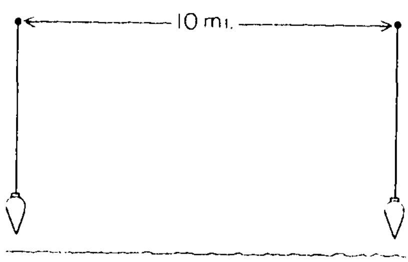
You indeed pull upward on the earth as strongly as it pulls downward on you. But the mass of the earth is many, many times greater than yours. So its upward *acceleration* is many, many times smaller than your downward acceleration. The earth doesn't come halfway up to meet you.

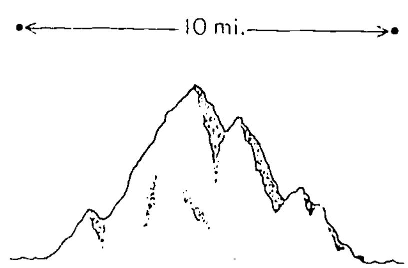
Try to imagine all three billion people of our planet climbing to the top of a tower that is one mile high. Then they jump off all at once. The earth doesn't come halfway up to meet them; it is so massive that it only moves upward a few billionths of an inch while the people are falling the mile.

GRAVITATION CLOSER BY

Newton solved the puzzle of why things move as they do—here on earth and far off in space. As you have seen, most of his reasoning was based on the motions of very distant objects—moon, sun, and planets. In his day, the only pertinent earthly quantity that could be measured directly was the acceleration of objects near the earth—32 ft/sec each second. With just this one number in this very small part of the universe, plus his limited knowledge of faraway celestial bodies, he invented a complete theory of gravitation.

But in later years some scientists wondered if there might be additional earthly evidence of gravitation at work. In the 1770's the British astronomer Nevil Maskelyne (MASS-kuh-line) thought of a possibility. To get started, he imagined two identical plumb lines suspended ten miles apart on a flat earth. Nothing was in between. When the masses stopped swinging in this imaginary situation, you would expect them to look as you see them in the drawing on the left. Why?

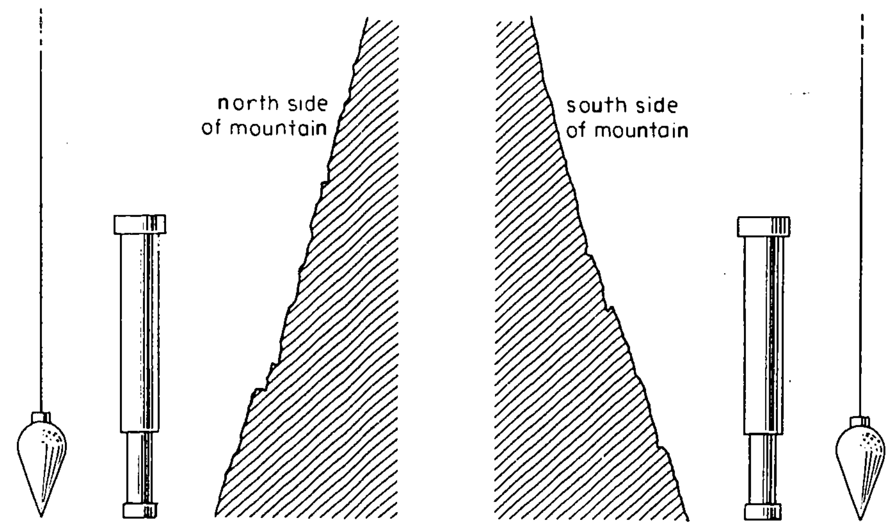




Next, he imagined there was a large mountain between the suspended masses. He had a hunch that they would not point in exactly the same direction as before. Can you guess what he thought? Explain why. Describe how the plumb lines would behave.

Maskelyne knew that a telescope pointing upward could be placed parallel to either plumb line. He guessed that when the telescope was placed parallel to the plumb line on one side of the mountain, it would not point to exactly the same spot in space as when it was placed parallel to the other plumb line.

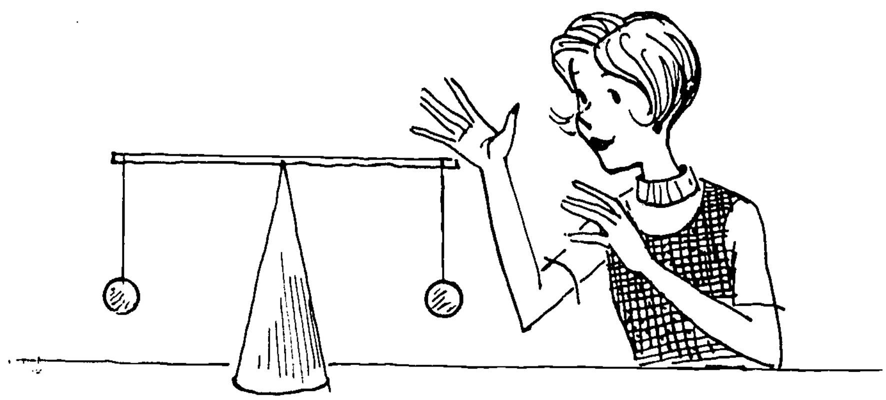
Then Maskelyne performed the experiment. He took into account the earth's curvature and all other effects that might give him trouble. One evening he set up his telescope north of the mountain and sighted it very carefully on a star crossing the zenith. The next night he set his telescope south of the mountain and watched the same star crossing the



zenith. Its position in the telescope was not quite the same. Could the mountain's gravitational attraction be affecting his measurements? Maskelyne figured carefully and was able to show that the mass of the mountain did indeed exert a gravitational force.

Some years later, around 1800, Henry Cavendish of England was able to measure the effect of gravitation between bodies of ordinary size. He made equipment in his laboratory, worked very carefully, and made precise measurements.

To help you understand how Cavendish found a way to measure the effect of gravitation, work this thought experiment. Spheres of equal mass are mounted at each end of a rod. The rod is adjusted so that it is perfectly level.



Now without changing anything else, place a large massive sphere under one end of the rod as in *Figure 1*. After a time, what happens to the rod? Will it remain level? Why? What is missing in *Figure 2?* What will happen to the rod in *Figure 3?*

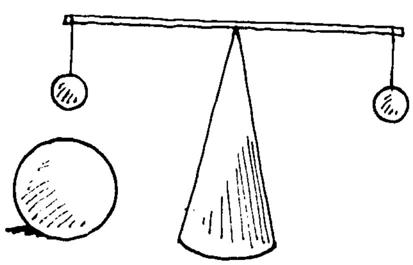


Fig. 1

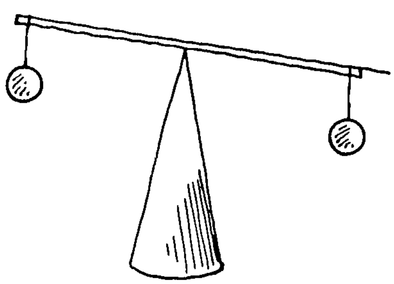


Fig. 2

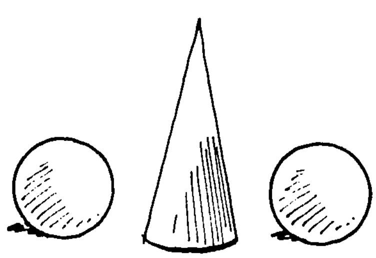
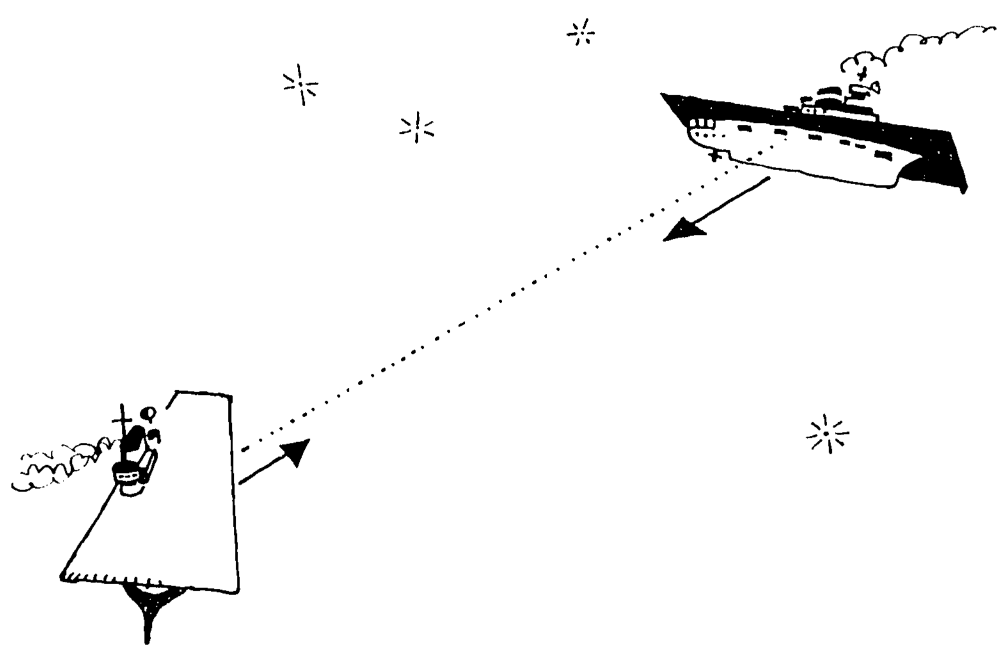


Fig. 3

Here is gravitation at work before your eyes. But this experiment is very difficult to perform because the force of attraction between the various spheres is extremely small. For example, take a pair of golf balls and put them two feet apart in space, motionless. The force of attraction would be so weak that it would take them two full days to come together. And if you could put two large aircraft carriers in space a world apart—8000 miles from each other—it would take about 100,000 years for them to collide.



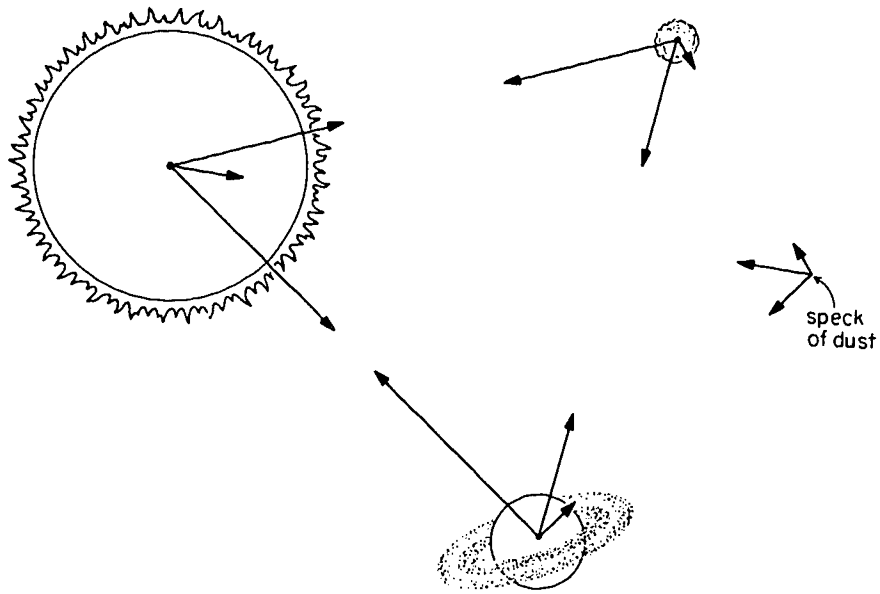
OUTWARD

You have seen how Isaac Newton, with help from Galileo Galilei before him, found some general rules about motions and forces of all kinds. If no net force is exerted on an object it continues to move in a straight line. If there is some net force exerted on an object its velocity changes; it accelerates. If you push a wagon eastward with a certain strength, how does the wagon push you?

You have also learned how the force of gravitation works—how it rules the motions of an apple or the moon, and how it rules the motions of the planets around the sun.

Newton looked elsewhere in the universe as it was known in his day. The satellites of Jupiter discovered by Galileo were continuing in their orderly orbits around that planet. And in Newton's lifetime five satellites had been discovered moving around Saturn. All these celestial bodies were moving as they should, responding to the force of gravitation.

The final leap that Newton made was to guess that the force of gravitation works wherever there are material objects. Every piece of matter in the universe—star, sun, speck of dust—attracts every other piece of matter.



And so Newton's universal law of gravitation was born. From that day until this, scientists have known *how* gravitation works. They can make predictions where Mercury will be twenty days from now, or tell just where the moon was 487,329 years ago today. Newton's theory tells us very precisely *how* gravitation works. And so it is curious to some that even today we do not really know *what* causes a gravitational attraction between objects. We know what an apple is; we know what a moon is; but nobody knows what gravitation truly is.

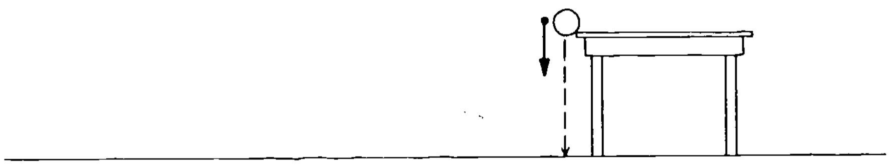
CHAPTER 8

Orbits Near the Earth

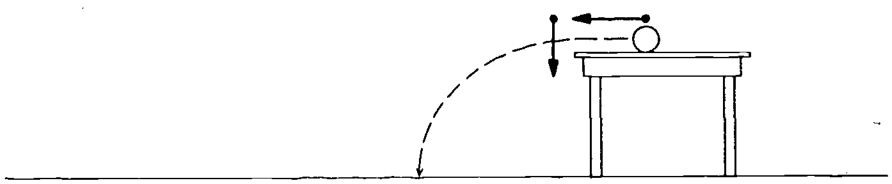
IN CLASS AND INTO SPACE

Roll a rubber ball at different speeds across a table. Observe the path of the ball as it goes over the edge.

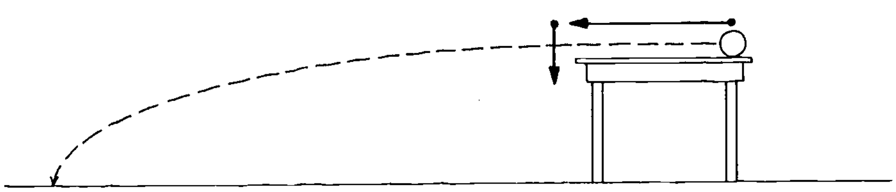
1. Start with zero horizontal speed by simply letting the ball drop off the edge of the table. What kind of path does the ball take?



2. Roll the ball horizontally at slow speed. The ball crosses the table, but at the instant it is launched off the top, it accelerates toward the earth. It moves horizontally a little way and at the same time curves downward, following a path that is part of an ellipse. When the ball is launched horizontally, the launching point is the farthest distance of the ball from the center of the earth. The high point is called the *apogee* (AP-eh-jee) of the orbit.

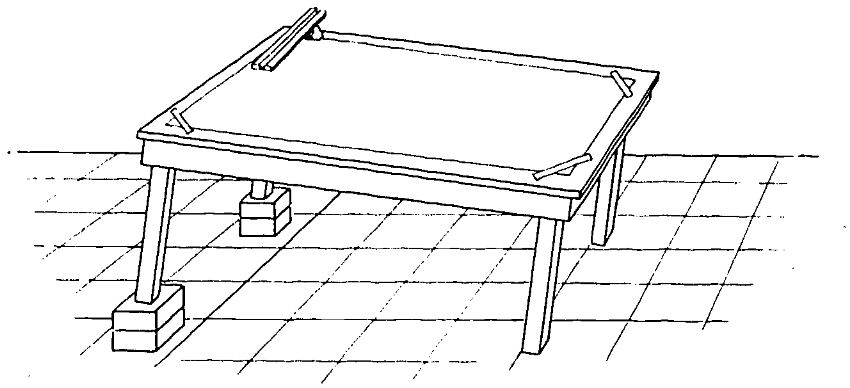


3. Roll the ball horizontally at high speed. The path after launch is part of a bigger ellipse. The ball flies farther before striking the floor. Again the launching point is the apogee of the orbit.



Does the ball move too quickly for you to watch its path? You will have more time to study the motions in the next activity.

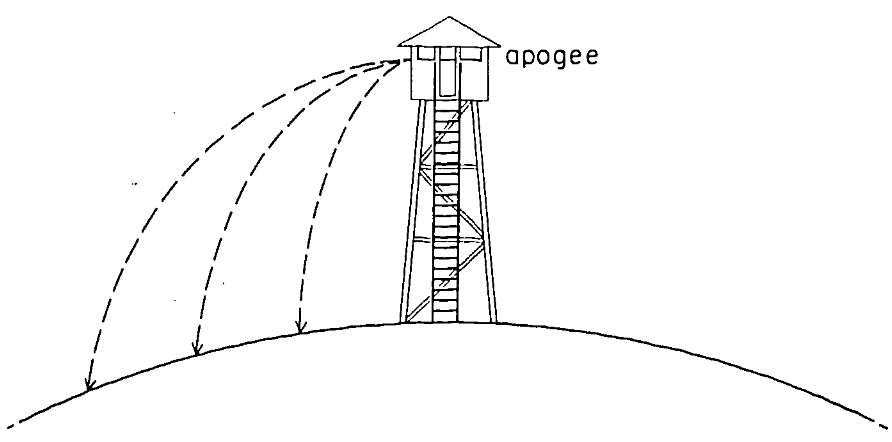
Tape large pieces of black construction paper to a table top. Raise one end of the table about four inches. Mount a grooved ruler near the higher end of the table as shown. Tilt the ruler to form a ramp. Keep the ruler fixed in position with small lumps of clay.



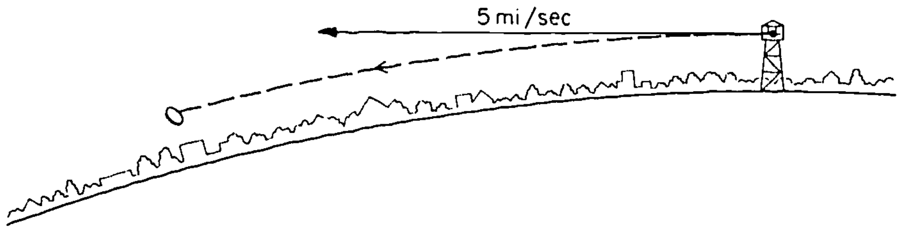
Roll a marble or steel ball in some talcum powder. Place the dusted marble about 2 inches from the bottom of the ramp. Let the marble roll. When the marble leaves the end of the ramp it should be traveling at a slow speed.

As the marble rolls across the paper it leaves a curved track. Notice the shape of the track.

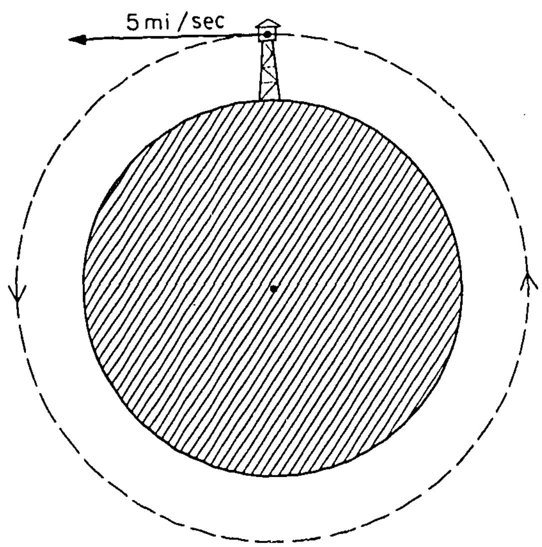
Next place the marble higher on the ramp so that it rolls off the ruler with a greater speed than before. Repeat this activity a number of times. Launch the marble with different speeds and compare the tracks. How does the launching speed seem to affect the path of the marble?



Now imagine you have a slingshot that lets you shoot pebbles at any speed you want. Go to the top of a very high tower so that buildings and even mountains won't be in the way. Shoot the pebbles faster and faster so they go farther and farther before hitting the ground.

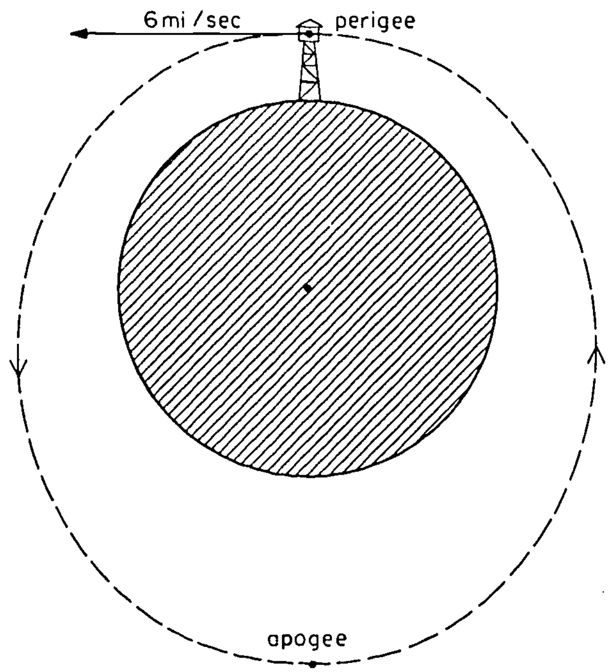


Imagine a launching speed of 5 mi/sec. Each second the pebbles move horizontally five miles. At the same time it also is falling toward the earth in a curved path, accelerated by the force of gravity. But mile after mile the earth's surface also curves, so the pebble never gets any closer to the ground. Do away with air resistance and the pebble goes around and round the earth in a circular orbit. At 5 mi/sec it circumnavigates the globe in a near-perfect circle every 84 minutes.

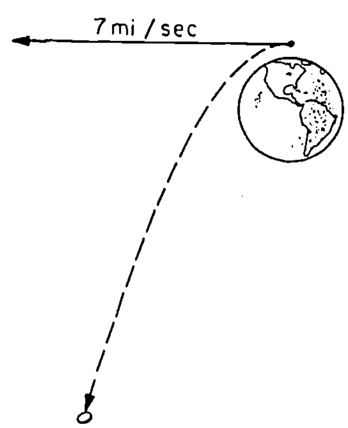


In this way satellites are launched into orbit around the earth. Rockets accelerate the satellite to a velocity of at least 5 mi/sec in a horizontal direction. When the satellite is sprung loose, it continues to move around the earth without need for fuel. It obeys the same rules the moon does.

Next, imagine launching a pebble with a greater horizontal velocity. At 6 mi/sec it moves along a larger orbit. The path is again an ellipse, but this time the pebble's closest point to the earth—the *perigee* (PAIR-eh-jee)—is at the slingshot.



Is it possible to shoot or launch something at such a fast speed that it will never come back to the earth? Shoot the slingshot horizontally at 7 mi/sec. The pebble escapes the earth forever. No matter how far away the pebble travels the earth continues to pull back on it. But the earth's gravitational force cannot slow it down enough to make it return.

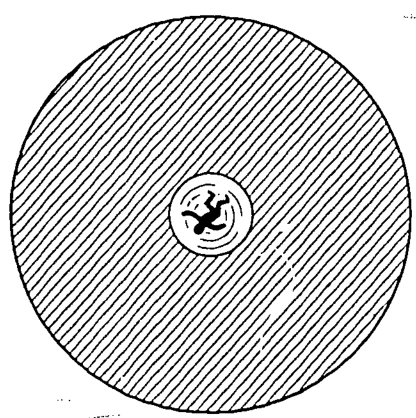


When the pebble is several times as far away as the moon, the more massive sun will take gravitational control of it. The pebble will go into an orbit around the sun in the same way that a number of spacecraft have been launched into solar orbit. The pebble will become a tiny new planet in the solar system.

Imagine one last shot—at 1000 mi/sec. This time the pebble leaves the neighborhood of the earth very quickly. It has such great speed that not even the sun's gravitational force can hold it in the solar system. In a few weeks it moves out beyond the orbit of Pluto. The pebble slows down a bit and curves slightly because of the back pull of the sun, the earth, and the other planets. But not much. It has a one-way ticket outward. After thousands of years you will find it out among the stars, moving in a straight line at constant speed away from the solar system.

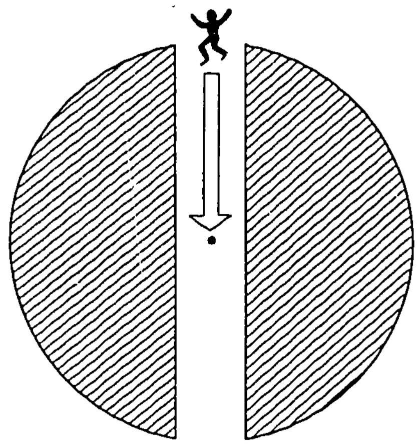
AT THE CENTER OF THE EARTH

Imagine being in a spherical hole at the very center of the earth. No longer are you at the surface where the acceleration of gravity is 32 ft/sec each second. Nor are you twice as far from the center, where the gravitational acceleration is only one-fourth as much. Do you think the force of the earth's gravitation would be very strong at the center of the earth? How would you begin to move? Puzzle it out.

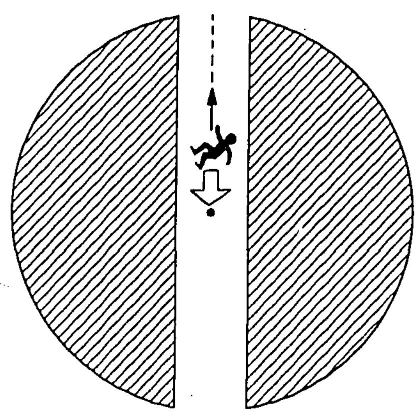


HOLES AT THE POLES

Now think about a very unusual kind of orbit. Imagine that you can dig a hole straight down into the earth from the North Pole through the center and on to the South Pole. Forget about cave-ins and the rushing of air into the hole. Imagine you simply have a straight tunnel going pole to pole without any air in it.



Step into the hole at the North Pole. Can you guess what will happen to you? What is your acceleration at the start? Later on you have left some of the mass of the earth behind you. It is pulling backward on you, opposing the forward pull of the matter ahead of you.

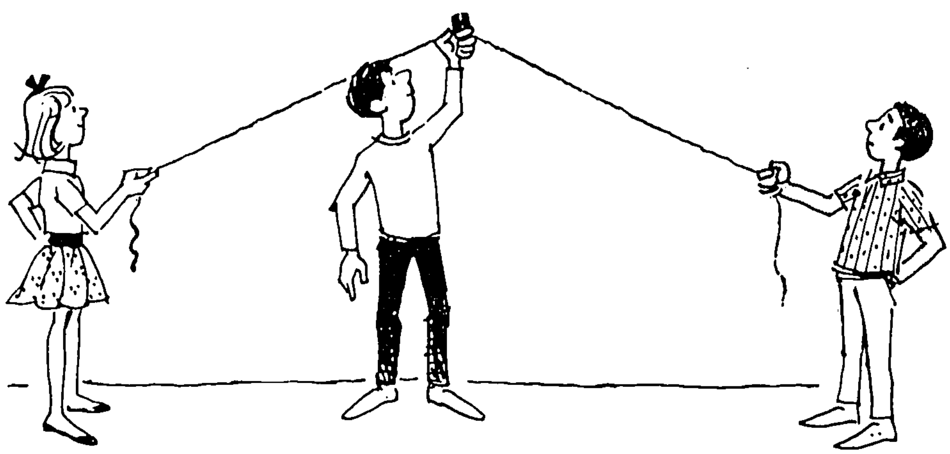


When you reach the center, everything is in balance and there is no net force acting on you. But you are moving very fast, so you overshoot and continue on toward the South Pole.

Then you are gradually slowed down because there is increasingly more of the earth's mass behind you. Finally you come to a halt at the South Pole. But if there is nothing to hook on to, it will be goodbye again. You will move back to the North Pole, then to the South Pole again, and so on—forever. Your round-trip orbital period would be somewhere between 60 and 84 minutes. Scientists cannot say precisely because the exact arrangement of rocks and iron in the earth's interior is not yet known.

To help you imagine what would happen with a hole connecting the poles, try this activity.

Tie rubber bands end to end until you have a string of rubber bands about 8 feet long. Fasten an old flashlight battery or a group of washers at the center of the string. With a classmate, hold each end of the rubber-band string so that it is slightly stretched. Have someone else raise the weight straight up as high as your heads and then let it go. Watch the motion of the weight.

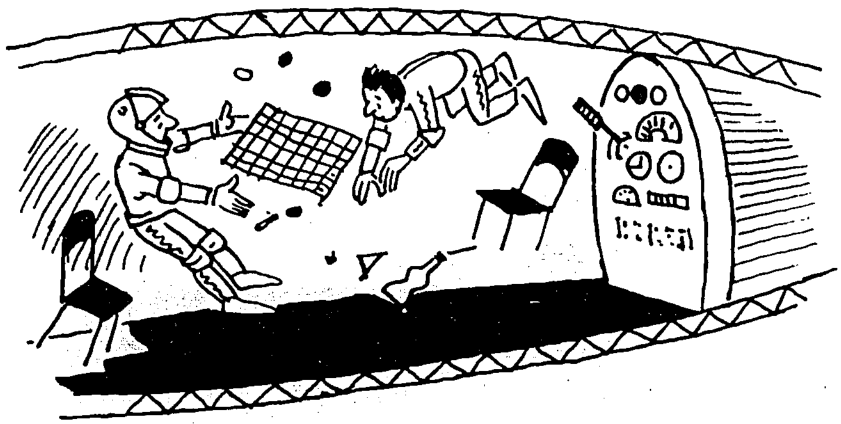


Repeat this activity several times. Keep the weight moving up and down.

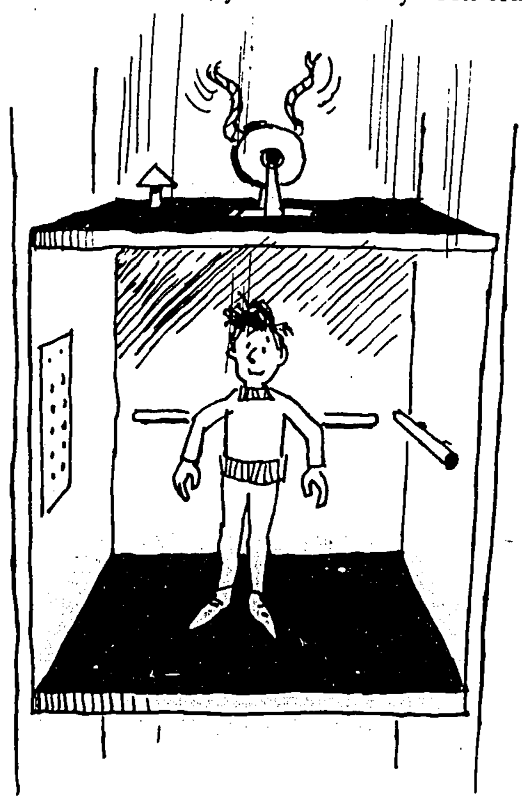
Where is the net force exerted by the rubber band on the weight the greatest? Where is it the least? In what way is this activity similar to the motion you imagined while falling from pole to pole? How is the motion different?

AFLOAT IN SPACE

Aboard a capsule orbiting the earth or a spacecraft cruising to Mars, you and every other unattached object inside the craft float freely. From the law of gravitation you know that the ship around you exerts *some* net gravitational force on you. But it is very small indeed and has practically no effect. Your spacecraft is moving along, responding to the combined gravitational force of all other objects in the universe. Its orbit is a result of all the gravitational forces of sun, earth, Mars, moon, and any other large nearby celestial masses.

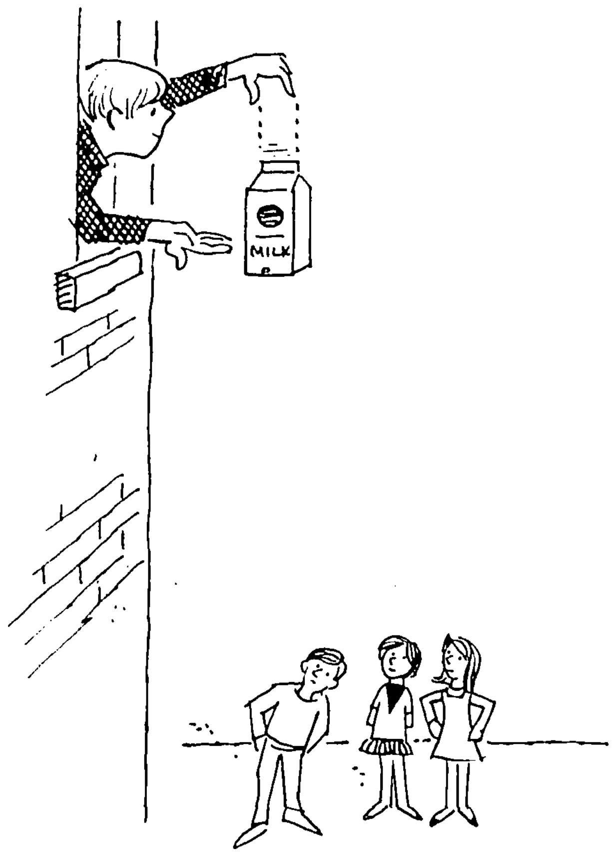


You are within the spacecraft, in the same position in space. The gravitational forces that accelerate the spacecraft accelerate you, too, in exactly the same way. At any instant your velocity is the same as that of your spacecraft. If it weren't, you would very soon crash into a wall of



the ship. But you don't because you move in precisely the same orbit as the spacecraft surrounding you.

Think about being in an elevator in a tall building. The cable snaps. You and the elevator are accelerated by gravity in the same way. So you float freely in the elevator while it plunges toward the ground. But watch out for the big bump.



When you place two objects in the same free-fall orbit near the earth, you can observe what happens to each of the objects.

On the side of an empty milk carton, near the bottom, punch a small hole with a pencil point. Climb to a high place. Cover the hole with a finger and fill the carton with water. What will happen when you uncover the hole? Try it. Observe the stream of water.

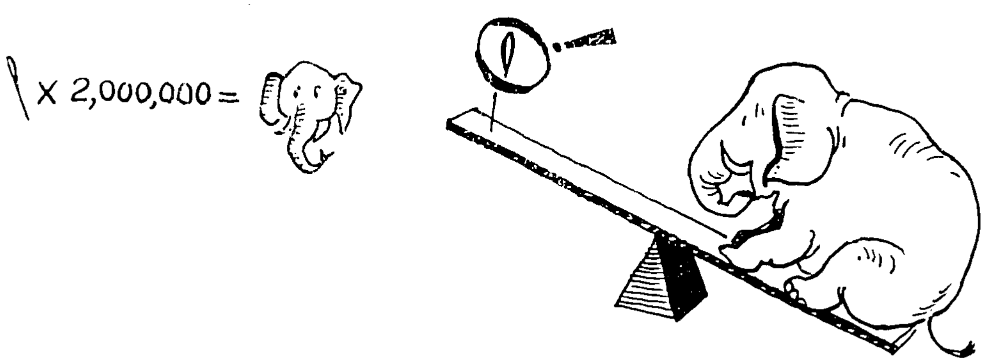
Cover the hole again and refill the carton. Hold the carton out so it will fall to the ground without hitting anything on the way down. Uncover the hole at the same instant you release the carton. What happens to the water in the carton?

Try again with another carton. But this time let the water flow out of the hole for a second or two before you let the carton drop. Then let it go. What happens to the stream of water when the carton begins to fall?

How does the orbit of a water droplet inside the carton resemble the orbit of the falling carton? Can you explain why?

WEIGHT—HERE AND NEARBY

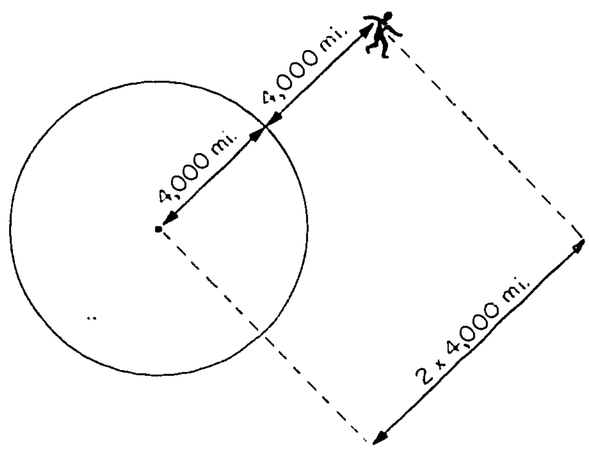
You know the acceleration of gravity is the same for an elephant as for a needle, but one has about two million times the mass of the other. On which is more force exerted? Which weighs more? If you put them at opposite ends of a seesaw, you know what will happen. And you also know why. The *weight* of any object on earth is the strength of the gravitational force exerted by the earth on the object. So long as elephant and needle stay at or near the earth's surface, the weight of the elephant is far greater than the weight of the needle. The weight of a pig is more than that of a fig. On the surface of the earth, weight is directly related to mass.



What happens to the weight of an object when it is not at the earth's surface? Go first to the center of the earth. Your mass is unchanged whether you are in the classroom or at the center of the earth. But at the center of the earth your weight is zero. Why?

Suppose you were 4000 miles above the earth's surface. At that distance you are twice as far from the earth's center as you are on the surface. You know that the force of gravitation is related inversely to the square of the distance. At that distance you would weigh one-fourth your weight on the surface. Figure out your weight at an altitude of 4000 miles.

You know that the mass of any object remains constant so long as nothing is removed or added. But now you have found that weight is not constant. Weight depends on the strength of the gravitational force pulling you.



Try these problems to help you understand the difference between mass and weight.

1. Suppose a cork ball has a mass of 4 grams. Home base for the ball is Kansas City. Then it is moved to Tokyo, Japan. Next it is 4000 miles above Valparaiso, Chile. Finally it is at the center of the earth. Does the mass of the cork ball change? Would its weight be the same in each location? Explain why.
2. The ball is moved to the center of the earth and cut into two equal parts. How does the combined mass of these two parts compare with the mass of the ball when it was in Kansas City? How does the total weight of the two parts compare with the weight of the original ball?
3. Consider one-half of the original ball. Compared to the whole ball, what is its mass 8000 miles from the center of the earth? What is its weight? Move this part of the ball still farther from earth. What happens to its mass? What happens to its weight?

WEIGHT—FAR OUT

Now imagine that you are taking a very long trip out into space. Suppose you call your weight 100 units when you're at the surface of the earth.

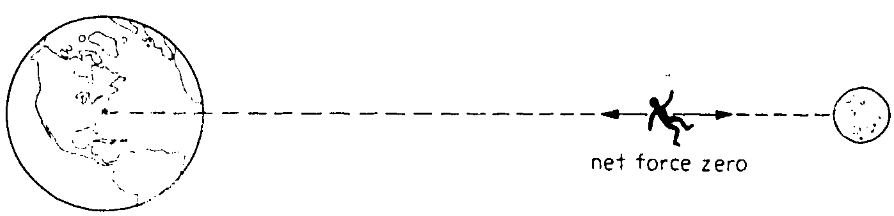
How many units would you weigh at different distances from the earth's center? Make up a table like the one below on a separate sheet of paper. Fill in the blank spaces in your table.

Distance from Center (miles)	*Earth Radii*	*Weight (units)*
4000	1	100
8000	2	
20.000		
		1
200.000		
400.000		

Throughout the trip your mass remains the same, but your entries in the table suggest that your weight becomes extremely small if you go very far from the earth.

Next, take another very long cruise into space. But this time set your course so you are always located on the line between the earth and the moon. As you move away from the earth, the moon is always in the direction in which you are heading.

At some point in your journey, as the moon grows larger and larger in the dark sky, its pull on you becomes just as strong as the backward pull on the distant earth. The gravitational forces are balanced, the net force on you is zero. Your weight, arising from the combined pulls of earth and moon, is zero. At this point in space you are weightless.



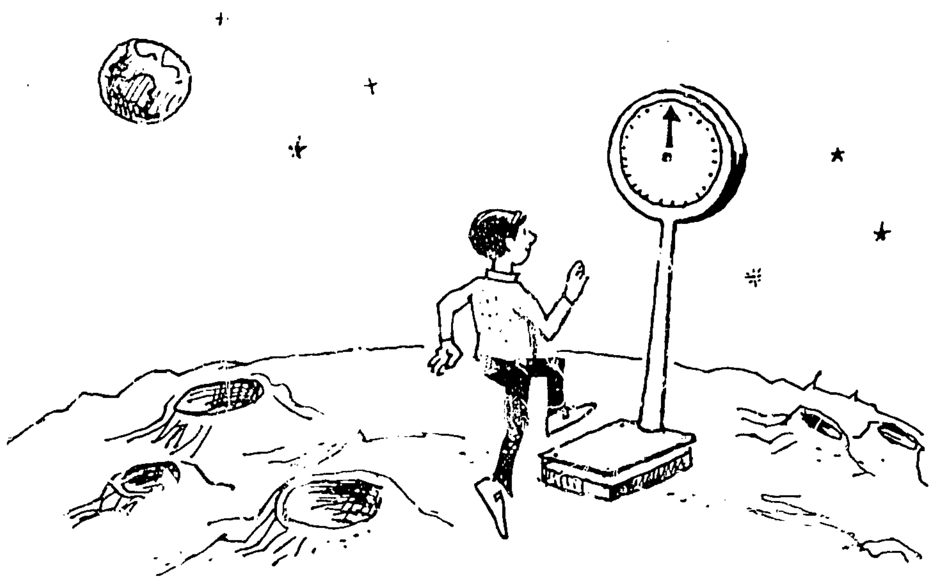
Face back toward the earth and sneeze. For a second or two you are a weak rocket. The force from your blast starts you falling toward the moon. Now the moon's pull on you gets stronger than the back pull of the distant earth. You accelerate. You move faster and faster and finally hit the moon at high speed.

Pick yourself up, brush off the moondust, and throw a rock upward. It goes surprisingly high and then slowly falls back to the ground. Why? You feel different. Why?

On the surface of the moon you're in a region where the earth's gravitational pull on you is so small that you can forget about the earth's effect on you. In comparison, the moon's pull on you is hundreds of times stronger because you are so close to the center of the moon.

WEIGHT—ON THE MOON

Figure out how much you weigh on the moon. Forget about the pull of the earth 240,000 miles away. Assume you are wearing the same clothes you have on now so that your mass remains the same. You know, of course, that you would need a space suit for breathing and protection. But forget those matters, too, and consider your mass is the same on the moon as it is here on earth.



Your weight at the surface of any celestial body is the strength of the gravitational force exerted by that body on you. Compare the strength of the *moon's* pull when you are *there* with the *earth's* pull when you are *here*. Your mass is the same in both places, so that's no problem. But when you stand on the moon, you are pulled downward by a body that is only about one-eightieth as massive as the earth. So on that count your weight should be only one-eightieth of its value here on earth.

But remember that the distance from the center of an attracting body also figures in the law of gravitation. The radius of the moon is only about one-fourth that of the earth. In other words, you are four times closer to the center of attraction. And from the inverse square law you should find that the force of attraction is 16 times stronger on the moon's surface.

Taking both effects into account—mass and distance—you find your weight is about one-fifth of its value here on earth. With more accurate figures, the value would come closer to one-sixth.

$$\frac{1}{80} \times 16 = \frac{16}{80} = \frac{1}{5}$$

On the moon you can jump six times as high as you can here—and it will take six times as long for you to come down to the ground again.

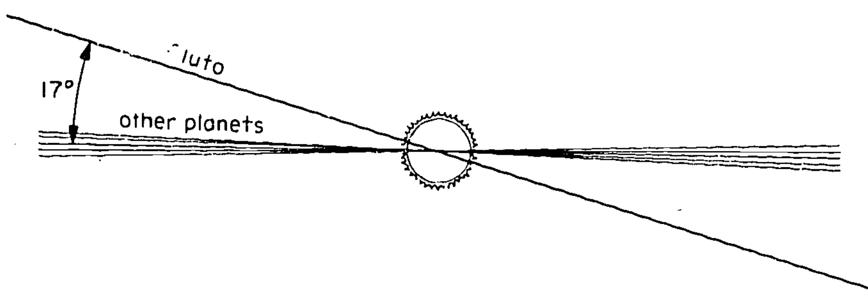
On a small asteroid your weight would be even less: you would have no trouble throwing a ball into an escape orbit. You could launch the ball into an orbit around the sun. On an even smaller asteroid—about one mile in diameter—you could jump off into orbit yourself.

CHAPTER 9

To the Planets

Our earth moves around the sun once each year at an average distance of 93 million miles. Its average speed in orbit is 66,000 mi/hr. At *perihelion* (pair-eh-HEE-lee-un), when the earth is closest to the sun, it is moving fastest—about 1100 mi/hr faster than average. At *aphelion* (eh-FEE-lee-un) half a year later it is moving slowest—1100 mi/hr less than average. Through half the year it slowly increases in speed as it approaches perihelion. Then, for the next six months, the earth decreases in speed as it moves toward aphelion. The earth orbits in this manner century after century, responding to the force of gravitation.

The motions of the other eight planets are also controlled by the sun's gravitational attraction. Their orbits resemble the earth's orbit in some ways. All are nearly circular ellipses, with most of the orbits lying in a flat, thin disk. A good model of the space through which the planets roam is the shape of a phonograph record. The only exception is Pluto, the outermost planet. Its orbit is rather elongated. In fact, when Pluto passes its perihelion every 248 years it is closer to the sun than Neptune ever is. But the two do not collide because Pluto's orbit is tipped out of the flat disk in which the other planets move.



The angle between the plane of its orbit and that of the earth's orbit is 17°. Furthermore, the path of Pluto is nowhere closer than 200 million miles to the orbit of Neptune.

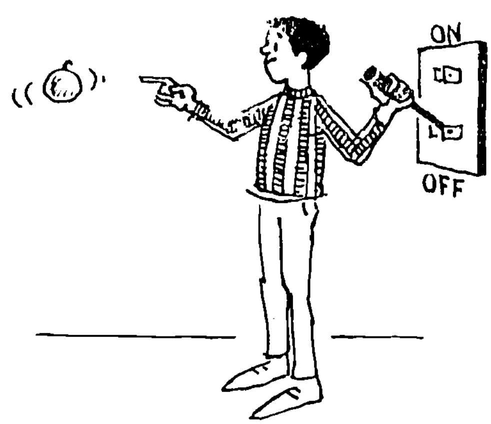
The table on page 88 gives you some information about the orbits of the nine principal planets.

TABLE OF PLANETARY ORBITS

Planet	*Average Distance from Sun (miles)*	*Orbital Period*	*Average Speed in Orbit (mi/sec)*
Mercury	36,000,000	88.0 days	29.7
Venus	67,200,000	225 days	21.7
Earth	92,900,000	365 days	18.5
Mars	142,000,000	687 days	15.0
Jupiter	483,000,000	11.9 years	8.1
Saturn	886,000,000	29.[illegible] years	6.0
Uranus	1,780,000,000	84.0 years	4.2
Neptune	2,790,000,000	165 years	3.4
Pluto	3,670,000,000	248 years	2.9

WITHOUT GRAVITATION

Gravitation binds the solar system together. What would happen without it? Suppose that we could turn off gravitation. Nobody can do it, but you can imagine some of the things that would happen if we could.



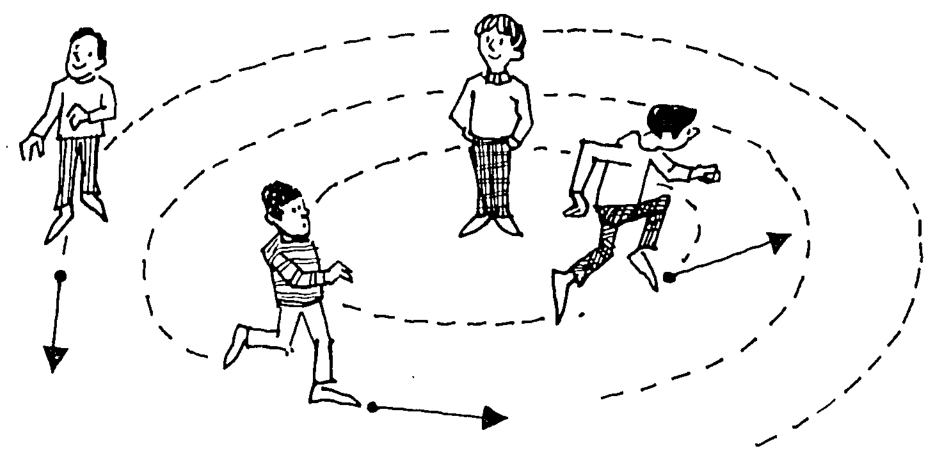
The instant before we decide to turn off gravitation, a snapshot of the solar system would show the bright central sun and each of the nine planets at some point in its orbit. Each moon would be at some point in its own track around its parent planet. And there would be other lesser bodies too—asteroids, comets, and so on.

Now flick the switch. No longer do the bodies of the solar system exert any forces on each other. What kind of path does each planet take? Why?

Which planet moves away fastest? Which slowest? After centuries go by, which is the closest planet to the sun? Is the earth still the third planet out from the sun? Work it out for yourself and then talk it over with your classmates.

In the schoolyard, make a walking model of these planetary motions. Form a group of four. One person stands still in the center of things; he is the sun. Closest to the sun is Mercury. He orbits at a very brisk pace. Then comes Venus, who walks a bit more slowly. Finally, earth moves even more slowly, third from the sun.

Gravitation is on. Put the model in motion so the planets are moving along in their orbits. On signal, turn gravitation off. Each planet continues moving at his own velocity. In what direction does each one go?

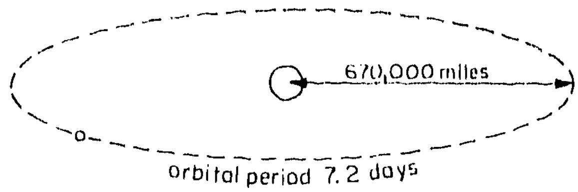


After about 15 seconds, stop all motion. Notice the positions of the participants. Is Mercury still closest to the sun? Is earth still farther from the sun than Venus is?

PLANETARY MASSES

Tycho Brahe (TIE-koe BRAH) made accurate measurements of the changing positions of the planets. Johannes Kepler used Tycho's data to discover some rules about planetary motions around the sun. And with a new invention, the telescope, astronomers could begin to measure the shapes and sizes of various planets. Now, with Newton's universal law of gravitation, it was possible to learn the masses of some of the planets.

For an example, think about the biggest satellite in our solar system—Ganymede. It travels around Jupiter in a nearly circular path every 7.2 days at a distance of 670,000 miles. Ganymede takes less time to swing around Jupiter than the moon does to swing around the earth. And you know why; Jupiter is far more massive than earth.



Imagine that we can change the mass of Jupiter. For a particular mass, the table below shows the orbital period of Ganymede if it moved in a circular orbit, always 670,000 miles from Jupiter's center.

Mass of Jupiter	*Orbital Period of Ganymede*
same as now	7.2 days
4 times now	3.6 days
9 times now	2.4 days
16 times now	1.8 days
¼ times now	14.4 days
zero	——

Why is no orbital period entered for mass zero? What would happen to Ganymede if the mass of Jupiter suddenly became zero—a huge ball of nothing?

From Kepler's third law the orbital period of any planet depends on its average distance from the sun. According to Kepler's law, the square of the orbital period depends on the cube of the average distance. In your example of Ganymede, the average distance is always the same, 670,000 miles. So from Kepler's law, the orbital period should also remain the same. But you found in the table that the orbital period would not always be the same. If it were possible to change the mass of Jupiter, the orbital periods would be different.

P = Period $\qquad D$ = Distance

$$P^2 \sim D^3$$

Was Kepler mistaken? Is his third law wrong? No. Kepler's law just doesn't explain the whole story. It doesn't take into account that the mass of a celestial object has something to do with orbital motion.

From the law of gravitation you remember that the more massive the planet, the greater the acceleration of its moon. So it seems perfectly reasonable to expect a satellite to orbit a very massive planet rapidly and to orbit a less massive planet more slowly.

Newton worked hard to find out exactly how the masses are related to the orbital periods. From Kepler's law and his own law of gravitation, Newton discovered a way to find the mass of a pair of celestial objects when two bits of information are known. Measure the orbital period of a satellite around its parent planet. Measure the average distance between the two bodies. With this information the combined mass of planet plus satellite can be calculated using Newton's formula:

$$M_1 + M_2 \sim \frac{D^3}{P^2}$$

Calculate the combined mass of the following planet-moon pairs. Use Newton's formula and follow the example shown for pair *A*.

Pair	*D*	*P*	$\frac{D^3}{P^2}$	$M_1 + M_2$
A	4	2	$\frac{4 \times 4 \times 4}{2 \times 2}$	16
B	2	2		
C	5	5		
D	2	1		

Which of the four pairs do you find to be the most massive?

Perhaps your answer is not surprising. Even though the satellite and planet of this pair are rather far apart, the large mass makes for a strong gravitational attraction. And so the satellite is whipped around in its orbit in a relatively short time.

For most pairs orbiting in the solar system — moon around planet or planet around sun — the mass of the lesser body is extremely small compared with that of the more massive one. So when you determine the combined mass of the pair, you come very close to finding the mass of the bigger body all by itself. After all, an automobile with a tennis ball sitting on the seat has just about the same mass as the automobile without a tennis ball in it. If the mass of car plus ball is 2056 pounds, you don't need to determine the mass of the ball to find that the mass of the car by itself is close to 2056 pounds.

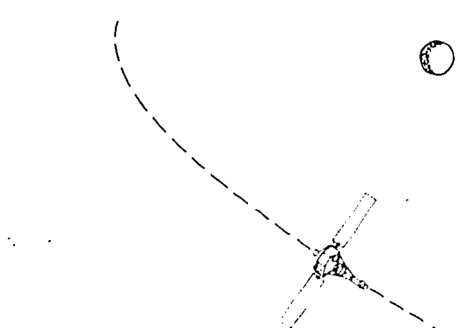
Data on Ganymede's orbit tell us that the combined mass of Jupiter plus Ganymede is 314 times that of earth plus moon. So the mass of Jupiter is also about 314 earth masses.

Here are the diameters and masses of the nine planets in units of the diameter and mass of the earth.

Planet	*Diameter*	*Mass*
Mercury	0.38	0.05
Venus	0.97	0.81
Earth	1.00	1.00
Mars	0.53	0.11
Jupiter	11.2	318.00
Saturn	9.5	95.00
Uranus	3.8	15.00
Neptune	3.5	17.00
Pluto	0.45?	?

Study the table of the masses of planets. Right away you probably realize that Newton couldn't possibly have used his formula to find the mass of every planet.

For one thing, some planets have no satellites at all so Newton's methods couldn't be used. Venus, for example, orbits alone in space under the gravitational control of the sun. But when, after Newton, astronomers observed the motions of planets near Venus, they noticed



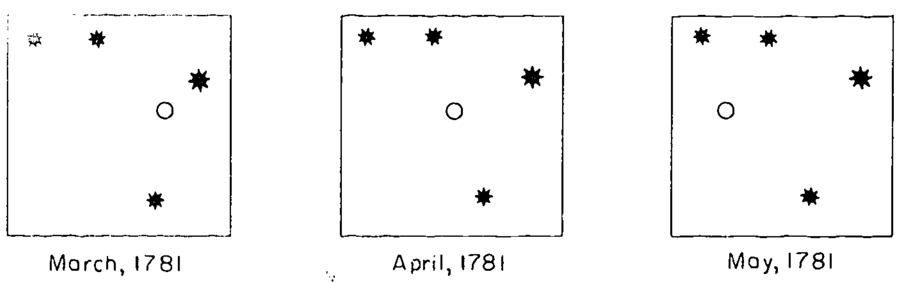
the tiny effects produced by the gravitational force of Venus. The neighboring planets were pulled slightly off their courses around the sun. By measuring these small gravitational pulls, it was possible to make a fair estimate of the mass of Venus.

In recent years, several spacecraft have been placed in orbits that carried them very close to Venus. From precise measurements of the tracks of these spacecraft as they passed the planet we now have a much more reliable measure of Venus' mass.

There was another reason, however, why Newton could not calculate the masses of all the planets. Can you guess why?

DISCOVERY OF THE OUTERMOST PLANETS

The night of March 13, 1781, marked the beginning of one of the most fascinating stories of astronomy. William Herschel (HER-shull), a British astronomer, was observing the starry sky with his seven-inch reflecting telescope. Everything seemed to be as usual. Countless tiny images of stars glided through the field of view as Herschel slowly turned the telescope. Suddenly he stopped. A strange object had entered the field, one that he had not noticed before. It could not be a star, for it was not a point of light. It was shaped like a tiny disk. Herschel thought he had discovered a comet.

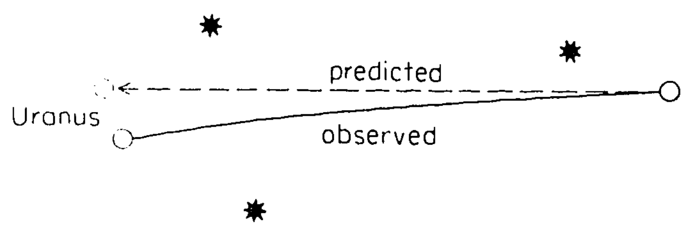


But he was mistaken. The greenish disk-like object which moved from night to night against the stellar background turned out to be something much bigger. It was a planet—the first planet discovered since ancient times. Herschel had added a new member to the family of planets already known to ancient astronomers.

British scientists were delighted with the discovery. And the king granted Herschel an income so he could continue his astronomical research. Herschel was very grateful and planned to call the new planet Georgium Sidus, after the king's name. But the planet later became known as Uranus.

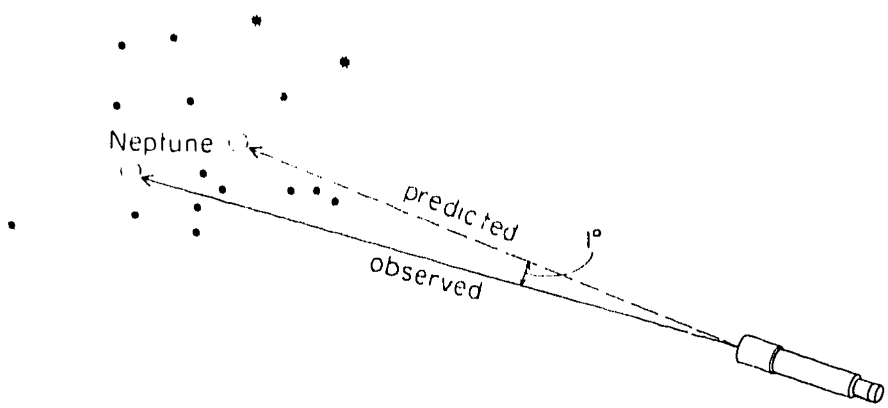
The discovery of Uranus turned out to be the first act of an exciting drama that developed in the following decades. Newton's law of gravitation was to have its most severe test.

The first test came after astronomers had used the laws of Newton and Kepler to calculate the orbit of Uranus. Observations of its changing position against the stellar background showed that Uranus was moving just as it should. All went well for a time. But as the years went by Uranus was not quite following its predicted path; there was no doubt about it. Did this mean that the universal law of gravitation was incorrect? Or was the path of Uranus disturbed by some strange effect unknown to astronomers?



In 1829, Bouvard (boo-VARD) of France had a hunch that the small disturbance of Uranus' motion was the result of the gravitational pull of an undiscovered planet in the neighborhood of Uranus. A few years later Adams in England and Leverrier (leh-VAIR-ee-ay) in France worked on this problem independently. They assumed that the disturbance in Uranus' orbit was caused by the gravitational pull of the unknown planet. Each spent several years calculating the exact position of this planet and the mass it must have in order to pull Uranus off course by the observed amount.

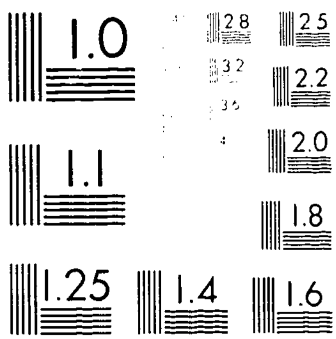
At first, all attempts to detect the suspected troublemaker were unsuccessful. But in 1846, after receiving a letter from Leverrier, the German astronomer Galle (GAH-leh) studied the skies looking for the predicted planet. In less than an hour of searching he found the planet in the constellation of Aquarius (eh-KWARE-ee-us), almost exactly in the position predicted by Leverrier. Here was another member of the solar system—the planet Neptune.



The discovery of Neptune was one of the most spectacular triumphs of astronomy in the 19th century. At the same time it was a brilliant proof of the universal law of gravitation. At first, credit for discovering Neptune was given to Leverrier and Galle. But since Adams also predicted the existence of Neptune, he shares the honors.

After Neptune had been discovered, the orbit of Uranus was computed all over again on the basis of the new data. Everything seemed to go smoothly for a while. But then a new puzzle arose. Even when the gravitational pull of Neptune was accounted for, Uranus still didn't quite follow the predicted path. What was the celestial trouble this time?

It was Percival Lowell, the founder and director of the Lowell Observatory in Flagstaff, Arizona, who predicted the existence of still another planet. But he died in 1916 without having discovered it in the sky. Fourteen years later, C. W. Tombaugh of the Lowell Observatory was comparing two celestial photographs that had been taken six nig' s apart. He noticed a faint image that had changed its position against the stars during this short period. It did not take long to show that the tiny dot on the photographs was the long-sought planet. It was in the con-



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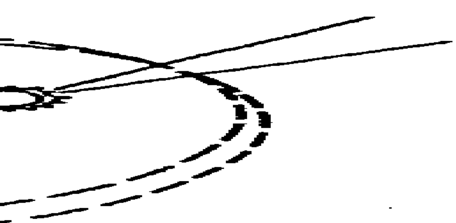
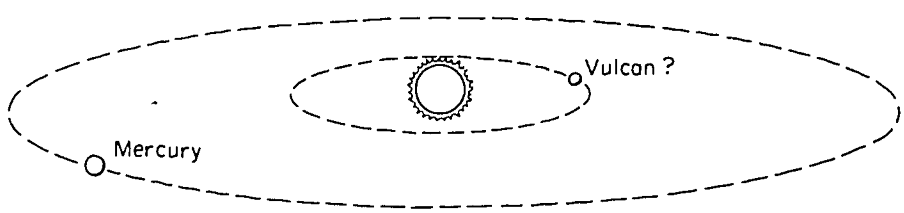


years

Mercury moves rapidly around the sun in an orbital path that resembles a somewhat elongated ellipse. Observations showed that the orbital path slowly turns in space. It rotates at the rate of 16 degrees every ten thousand years.

In 1845, Leverrier was quick to explain the reason for this slow turning motion. If the sun alone were pulling on Mercury, then the prediction of Kepler or Newton was that the long axis of Mercury's ellipse would point toward a fixed position against the background stars. But the sun is not alone. Venus, earth, and other bodies exert gravitational pulls on Mercury, too. And as the centuries pass, their effect on Mercury acts to make the orbit of Mercury turn slowly in space. Leverrier computed the rate at which Mercury's orbit should turn as a result of all these extra, weak pulls. The predicted rate was almost enough—but not quite. Mercury's orbit actually turns a bit faster than Leverrier predicted.

To explain the discrepancy, Leverrier suggested the existence of one or more unknown planets moving inside Mercury's orbit closer to the sun. His idea seemed to be supported by some early reports that a tiny black object had been observed moving across the face of the sun. If the reports were true, the black spot could have been such a planet. Some astronomers were so convinced a new planet would actually be found that the colorful name of Vulcan was assigned to it. But all efforts to find the planet failed. The reason was simple: Vulcan does not exist. What then caused the discrepancy?



More than 70 years were to pass before the answer was clear. The trouble lies with Newton's universal law of gravitation itself. Under normal conditions, celestial objects obey the law beautifully—just as Newton predicted. But for very fast-moving bodies, like innermost Mercury, the rules need to be changed somewhat.

The puzzling motion of Mercury's orbit finally was explained by the general theory of relativity, which was first given to the world by Albert Einstein in 1917. Relativity provides an even more complete theory of gravitation than does the work of Newton. Its predictions about motion

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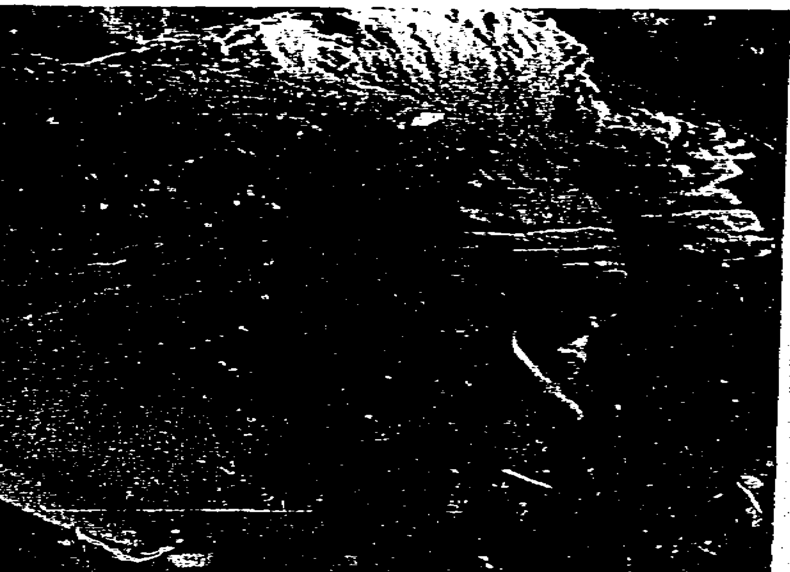

tein (1879-1955) spent many years
new physical theories.
theory of relativity extended
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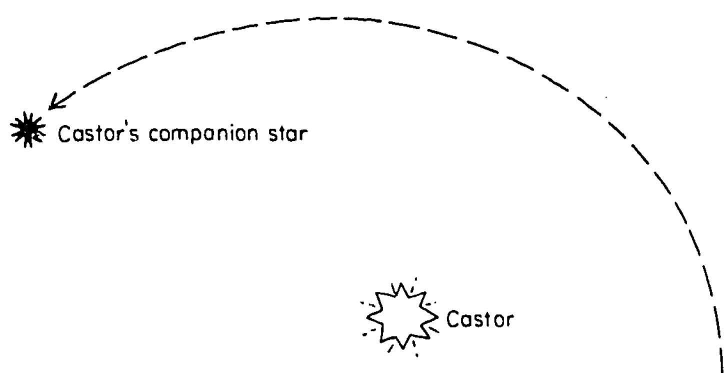
xplanation of gravitation.

CHAPTER 10

Out Among the Stars and Galaxies

A falling apple, the moon, the sun, and the planets all move under the control of gravitation. Does gravitation work also out among the stars? Newton believed that all objects, large or small, pull on other objects. He had a hunch that gravitational forces work throughout the universe. Yet more than 100 years were to pass before Newton's hunch was tested.

When Herschel discovered Uranus in 1781, he extended the horizons of our knowledge outward to 19 astronomical units from the sun. He also spent time studying the bright star Castor (KASS-ter), which appeared as two separate stars in his telescope. He observed the star-pair off and on



for a number of years. When he plotted its track, he found that the fainter star had been curving steadily around the brighter one, along an ellipse. Here was a distant star-pair obeying Kepler's laws. Gravitation was affecting the motions of objects far beyond the bounds of the solar system.

Herschel could only guess at the enormous distances of the stars. But we know today that Castor is nearly three million astronomical units or about 45 light-years from the sun. So Herschel showed that gravitation was at work more than a hundred thousand times as far away as Uranus.

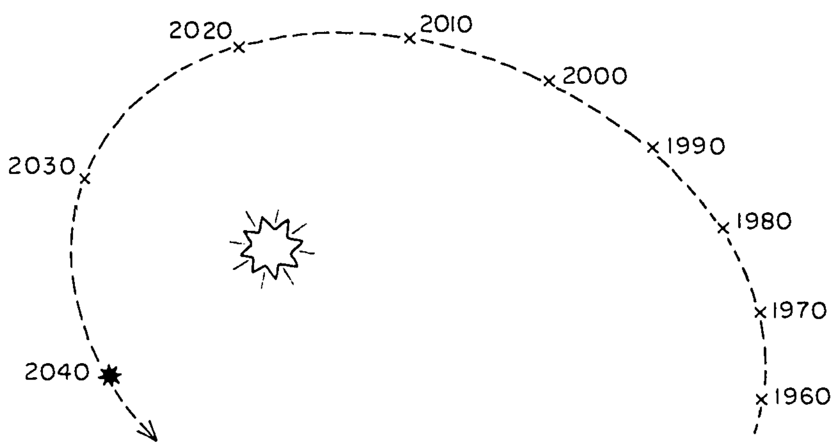
Many other pairs of stars are known, and for every pair that has been observed over a long period of time, the stars are found to be moving around each other obeying Kepler's laws. And if they are obeying

Kepler's laws, they must move according to gravitational pulls of each on the other. Here and there astronomers find trios of stars, and quartets, and even larger groups. Members of each group always move according to the gravitational rules.

STAR MASSES

Kepler's third law, as improved by Newton, can be used to find the combined mass of a moon and planet, or the combined mass of sun and earth. Can we find the masses of stars in this same way?

No isolated star exerts enough gravitational force on any other star to change its velocity noticeably. But with a star-pair, small changes in position may be observed from year to year. After many decades these small changes can be plotted to find the track of each of the stars. In every instance the fainter star is found to be moving in an elliptical path around the brighter one.



From a plot of the orbit it is possible to figure the orbital period. Then when you have also learned the average distance between the two, the combined mass of the stars can be calculated by Newton's formula.

In units of the sun's mass, the combined mass of a pair of stars equals the cube of the average distance between the stars, divided by the square of the orbital period.

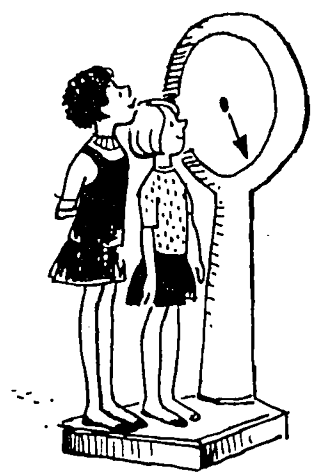
$$M_1 + M_2 = \frac{D^3}{P^2}$$

Suppose a star-pair has an orbital period of five years and an average separation of four astronomical units. Figure $(4 \times 4 \times 4) \div (5 \times 5)$. The answer is 2.56. So together both stars are 2.56 times as massive as the sun.

Now use Newton's formula to work out these examples.

1. A star-pair has an orbital period of 10 years. The average separation is 10 a.u. Find the combined masses.
2. Think of a different pair of stars. This pair is also separated by a distance of 10 a.u. But these two stars are found to have an orbital period of 20 years. Is this pair as massive as the other one? Does the law of gravitation give you a clue? First, make a good guess about the combined mass of this pair. Then, figure it out to see if your guess was a reasonable one.

You and someone else step on a scale together and the pointer shows 183 pounds. You know something, but perhaps not all you want to know. Who is the more massive? How would you find out easily?

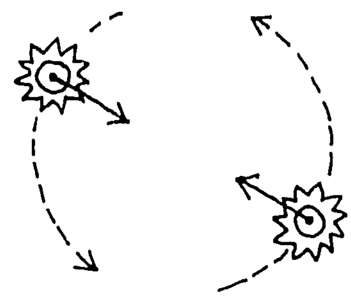


You can't place a star on a scale, but you know how to find the combined mass of a pair of stars. How can we determine the mass of each individual star is we know only the combined mass of both?

Remember in Chapter 7 when all the world's people jumped off a one-mile tower at the same time. The earth pulled downward on them, and they pulled upward on the earth with the same gravitational force. They both pulled on each other. And so the people were accelerated downward and the earth upward.

But the earth is more massive by far than all the people in the world. So it moves upward only a tiny distance to meet the falling crowd.

In the same way, earth and sun pull on one another with the same force. But since the earth is so much less massive, it is accelerated 330,000 times more than the sun.



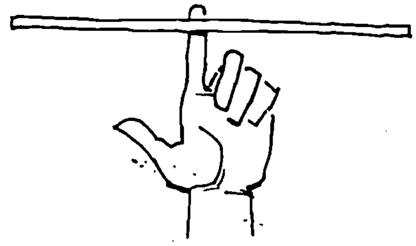
Think of two stars having equal masses, moving around one another in circular orbits. Who is going around whom? You know the forces are equal, but so, too, are the accelerations this time. On this celestial merry-go-round each star affects the motion of the other in the same way. Can you guess where the center of the merry-go-round would lie?

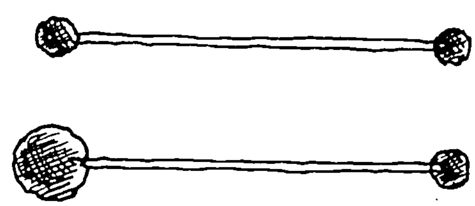
Make a start on this puzzle by working with masses stuck to the end of a wooden rod.

CENTER OF MASS

Find the balance point of a one-foot ruler. Where is it? Find the balance point of a yardstick. Where is it?

Now try the same thing with a straight wooden rod.



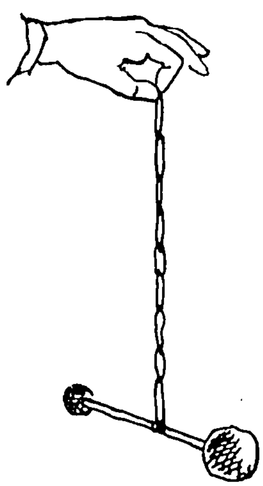


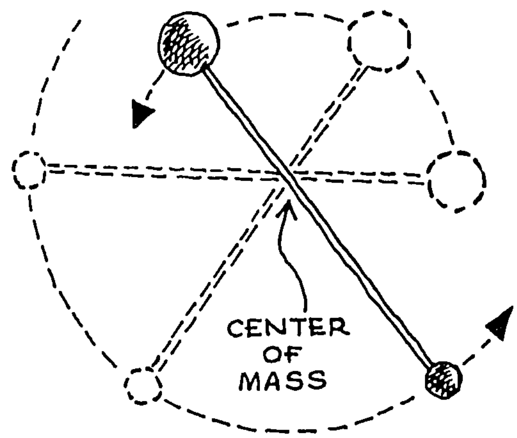
Next, fix two equal-sized pieces of clay to each end of the rod. Where is the balance point? Then stick a small bit of clay at one end and a big glob at the other. Where is the balance point now?

In each of these activities you have found a point where the masses are in balance. When is this balance point midway between the two masses? And when it it closer to one of the masses than to the other?

Now think of the stick and the globs of clay as a single mass. How can you find the center of the whole mass?

At each end of a stick place a lump of clay. One lump should be more massive than the other. Tie rubber bands together to form a string about 3 feet long. Attach the rubber-band string somewhere near the center of the stick. Notice what happens when the stick hangs freely.





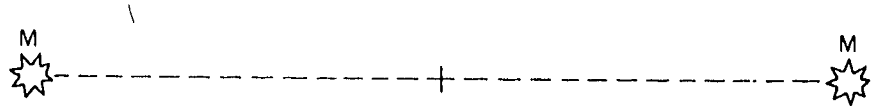
Now hold the stick in position and ask a classmate to start twisting the rubber bands. Have him keep twisting until the rubber band is nicely wound up. While he holds the rubber-band string, you let go of the stick. Watch the stick as it picks up speed. Can you see the center of mass?

Change the sizes of the clay globs and repeat this activity several times. Observe what happens. Can you find the center of mass each time? Is the center of mass always in the same place? What can you say about the center of mass when one of the objects is more massive than the other?

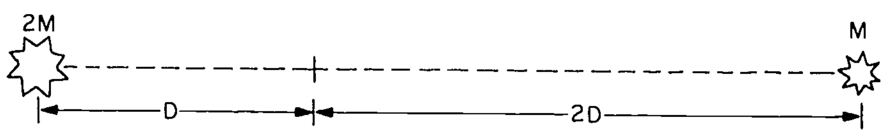
Although there is no solid matter connecting two stars, every pair of celestial objects has a center of mass. As with your whirling masses, the center of mass of any two stars lies along a straight line between the centers of the two stars.

To find the mass of each individual star, astronomers must find the distance between the stars. Then they must locate the center of mass of the star-pair. With this information they can find the relative masses of the stars — how massive the big star is in terms of the smaller one.

If two stars are equally massive, the center of mass lies halfway between them.



If the larger star is twice as massive as the smaller, the center of mass lies twice as close to the big star as it does to the smaller. If the bigger star is 9.414 times as massive as its smaller companion, the center of mass lies 9.414 times as close to the more massive body.



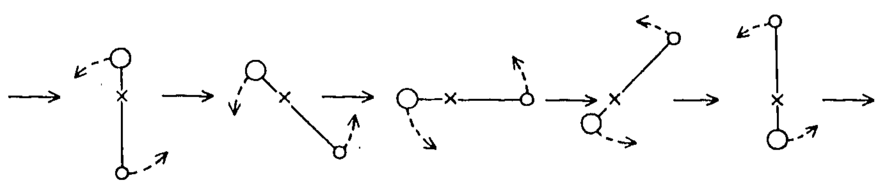
Remember that a single isolated star moves in a straight line at constant speed for centuries on end. But in a star-pair how does each member move? And what kind of track does the center of mass take?

Set up your equipment again the same way as in the previous activity. But this time attach the rubber band to the center of mass. Wind up the rubber band a bit, but not nearly as much as before. As soon as the masses begin to rotate, walk slowly and carefully in one direction. Watch the path taken by the individual masses. Are the paths the same? Which mass moves faster?

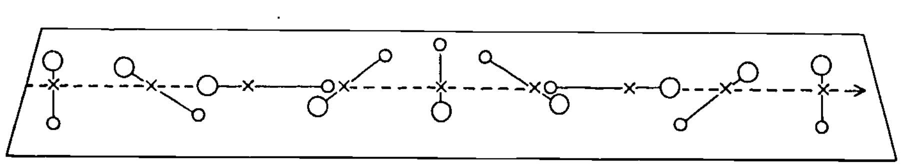
Now do it again, this time keeping your eye on the center of mass. How is it moving?

In a star-pair it is the center of mass that moves in a straight line at constant speed. You can't see the center of mass; you can only plot the

motion of each star of the pair for many years against the background of faint and distant stars. You know that the center of mass must always lie



on a line joining the two stars. And you know the center of mass must move straight at a fixed rate. You use these clues to find out how massive the big star is in terms of the smaller one.

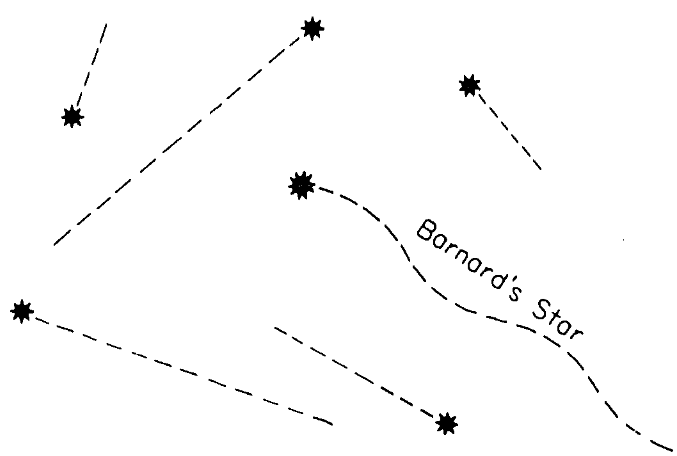


Sirius (SEER-ee-us) is the brightest star in the sky. In the 1840's Sirius was observed to follow a wavy motion against the background of distant stars. Astronomers suspected that an undiscovered companion star was affecting the path of Sirius. Yet almost twenty years passed before the faint companion was actually seen through a telescope. This star-pair is found to have an orbital period of fifty years and an average distance apart of twenty astronomical units. What is the combined mass of the star-pair?

The bright star, Sirius, lies about twice as close to the center of mass as does the feeble companion. What can you estimate about the mass of each of the two stars?

Astronomers have learned the masses of several hundred stars. They have found that the average mass of the stars is close to one-half that of the sun. A few stars are ten or more times as massive as the sun. But most stars are less massive than ours and some little ones have masses less than one-tenth of the sun's. The *sizes* of stars differ greatly from one another, and the *luminosities* of stars differ enormously. But the masses don't differ nearly so much.

In 1963 for the first time, a planet was detected outside the solar system. Barnard's Star, the second nearest star known, is a faint dot in the constellation of Ophiuchus (oh-fee-YOU-cuss). Its motion against the stellar background is not quite a straight line, but traces, instead, a very slight wave motion. One wave is completed every 25 years. The motion



must be caused by an invisible companion. It is possible to calculate from the motion of Barnard's Star that the companion, although never seen, has a mass only a bit more than Jupiter's. Since the companion is many times less massive than any known luminous star, it seems reasonable to believe that the invisible companion is a planet.

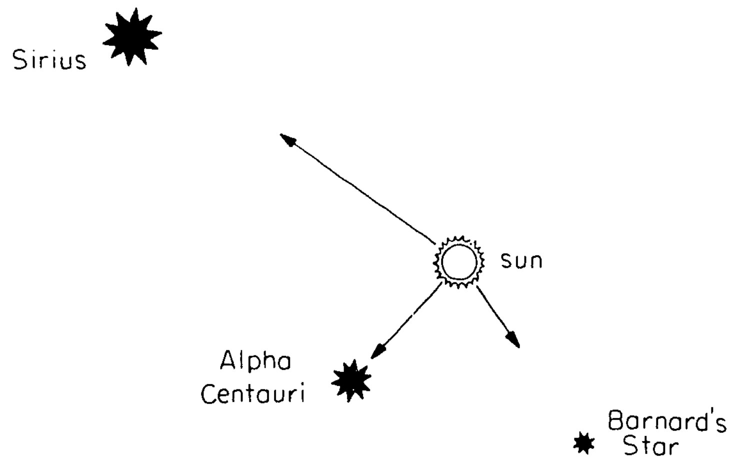
THE HOME GALAXY

Our Milky Way galaxy is a huge gathering of stars wheeling around in space. Approximately 200 billion stars dwell in a vast region of space shaped something like a pancake. Our galaxy has a diameter of about 100,000 light-years. Between the stars space is not absolutely empty. Perhaps one-hundredth of all the mass of the galaxy is in interstellar space, chiefly in the form of single atoms of hydrogen gas. But nearly all the rest of the matter in our galaxy is in the stars. Planets accompanying stars might account for a very small part of the mass, but astronomers know very little about planetary systems beyond our own.

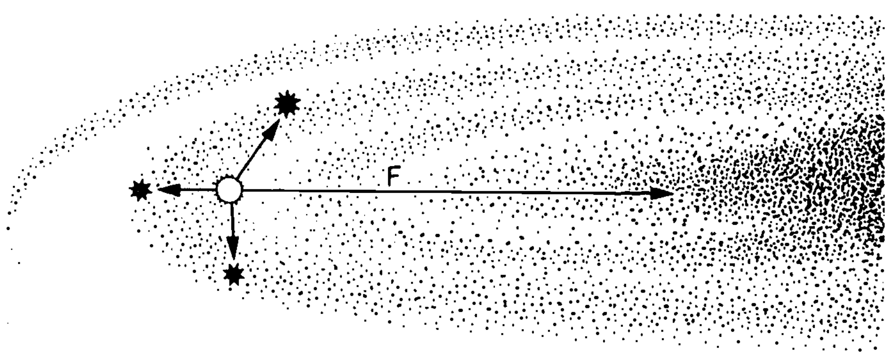
The Great Galaxy in Andromeda is similar to our own galaxy.
The two are about equal in size
and both have large spiral disks that bulge in the center.

In our part of the galaxy a star's nearest neighbor is about four light-years away. In the central part, the stars are more neighborly—about one or two light-years apart. But there is still plenty of room, so there is very little chance of stars colliding with one another even in the center of the galaxy.

Each star in our galaxy is moving in orbit along a path that is determined by the net gravitational force exerted on it by all the other stars in the entire galaxy. For example, think of our star—the sun. Alpha Centauri (AL-fa sen-TORE-ee), Barnard's Star, Sirius, and other nearby stars exert the greatest individual pulls on the sun. Because of their closeness their gravitational pulls are much stronger than those of distant stars. So it might seem that these nearby stars control the sun's galactic orbit.



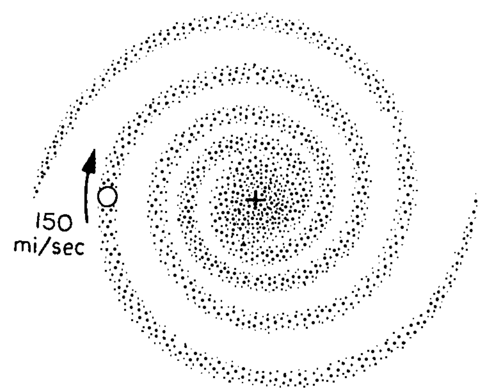
But there are two good reasons why this is not so. In the diagram above, see how the gravitational pulls of nearby stars tend to balance each other.

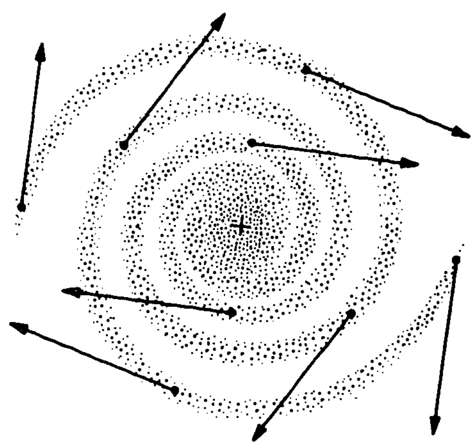


The chief reason that the nearby stars don't rule our galactic motion is that the billions of stars near the hub of the galaxy are all pulling together on us—pulling in about the same direction. The net gravitational force arising from the stars far away in the central part of the galaxy is about a thousand times as great as that arising from the pull of nearby Alpha Centauri.

The sun and solar system respond to this greater force by moving in a huge orbit around the center of the galaxy at a speed of about 150 mi/sec. Even at such a rapid speed, it takes us about 220 million years to complete one circuit around the center of the galaxy.

Turn off gravitation throughout the galaxy and watch what happens. Keep watching for a hundred million years. All the stars and atoms in the galaxy move out in straight lines into inter-galactic space. The galaxy is flying apart.





Now start over again with the galaxy as it is today. Leave gravitation on this time, but stop all of the stars in their galactic orbits so that each one sees all the others at rest. What happens then? See if you can tell.

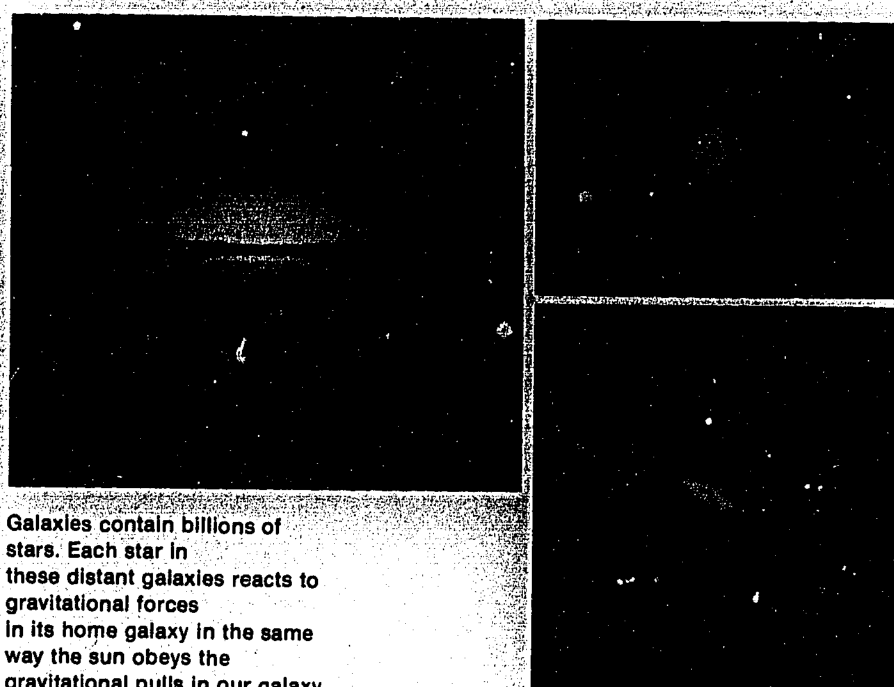
But with gravitation turned on and with the stars having the orbital motions they were born with, the galaxy neither shrinks nor swells; it neither flies apart nor collapses in a central heap. Our spinning galaxy will keep going for a long time. Even after the light from all the stars fades out, the stars will still retain almost all of their matter. The gravitational attraction of these dark masses on one another will continue on and on.

FAR OUT AMONG THE GALAXIES

The galaxies are the largest known star systems in the universe. A typical galaxy is a system of billions of stars. And every single star in a galaxy moves in a huge orbit around the galactic center, obeying the combined gravitation pull of all the other stars in its home galaxy.

In some galaxies the stars are arranged in great spherical regions. Other galaxies, like our own Milky Way system, are shaped more like pancakes or fried eggs; most of the stars are confined to a thin disk and move in roughly circular orbits around the central zone.

Many galaxies are isolated in space. But here and there one finds pairs, or triplets, or even larger groups called clusters of galaxies.



Galaxies contain billions of stars. Each star in these distant galaxies reacts to gravitational forces in its home galaxy in the same way the sun obeys the gravitational pulls in our galaxy.

Our own home galaxy has two relatively close neighbors—the Large Cloud of Magellan and the Small Cloud of Magellan, both easily seen from the southern hemisphere. These galaxies are about 150,000 light-years from here and about 50,000 light-years from one another. Because galaxies also exert gravitational pull on each other, the two Clouds of Magellan may orbit around each other. And at the same time they may go around or through our own Milky Way galaxy. Astronomers do not yet know just how the three of us are moving in relation to one another.

Our galaxy also belongs to a bigger group with seventeen known members, called the Local Group. Ours is a galaxy of the spiral type, and we rank second in size in our Local Group. Largest is the Great Spiral in Andromeda (an-DROM-uh-duh), barely visible to the unaided eye on a clear dark evening in autumn or winter. It is about two million light-years away. All the members of our Local Group influence each other's motions, but it is yet certain just how. The major effect on our galaxy's motion must arise from the pull of our massive spiral neighbor in Adromeda.

Huge clusters of galaxies, with hundreds of members in each one, are found here and there in distant space. Astronomers have been able to learn that the galaxies in those great clusters are moving around with speeds up to 1000 mi/sec or more.

These high speeds mean one of two things. Perhaps the galaxies of such a cluster are flying apart. Or perhaps the members are staying together but are wandering around among one another in response to the very strong gravitational pulls of the galaxies on each other. There may be some truth in both suggestions. But whatever the answers may be, it seems certain that galaxies in these great clusters must collide and pass through each other occasionally.

The universe, on its grandest scale, is expanding. In this biggest picture of all we can imagine the galaxies and clusters of galaxies become just points on an expanding balloon. The points are all moving away from one another as the balloon inflates. What could be the role of gravitation in this universe of fleeing galaxies? As with many things at the horizon of today's knowledge, this puzzle isn't yet solved.

Think about the riddle in two different ways. First, our galaxy, or any other galaxy, should somehow be able to exert a backward pull on distant galaxies. That back pull would slow them down, like a ball almost up at the top of its flight.

Second, think about one of those galaxies far, far out in space. Like our own galaxy, it feels pulls in all directions. It, too, is surrounded by other galaxies in all directions. And so there should be a tug-of-war in which nothing much happens. The galaxy may feel no net gravitational force on it, like a person at the center of the earth. Looked at in this way, the galaxy is not accelerated and so it just keeps going in a straight line at constant speed.

We are still not at all certain how gravitation affects the whole universe as the billions of years go by. But for all sorts of smaller objects you have seen how gravitation is a major ruling force in this universe of matter and mass—for galaxies in a cluster, for the stars in a galaxy, for a planet near a star, for our own moon, and for an apple that fell to the ground in an English orchard over three hundred years ago.